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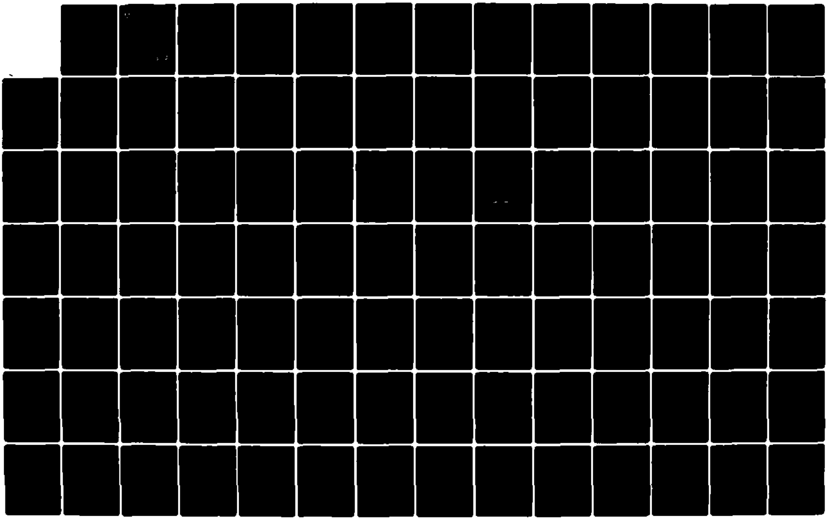

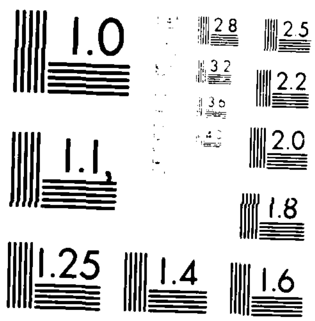

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RESEARCH AND DEVELOPMENT TECHNICAL REPORT

CECOM DRSEL-TR-78-2922F

AD A132007

ULTRA LOW LOSS OPTICAL FIBER CABLE ASSEMBLIES

Volume 1

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7635 Plantation Road, N.W.
Roanoke, Va. 24019

7 June 1983

Final Report for Period December 1978 - December 1982

Approved for public release; distribution unlimited.

Prepared for
CENTER FOR COMMUNICATION SYSTEMS
Ft. Monmouth, N.J.

CECOM

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FORT MONMOUTH, NEW JERSEY 07703

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This final report describes the development of tactical fiber optic cable assemblies. The effort was to develop a tactically deployable cable capable of a transmission rate of 20 Mb/s over 8 km repeaterless lengths. The optical performance required to meet the requirements is a dispersion of less than 2 ns/km and an attenuation of less than 5 dB/km at 0.85 μm combined with connector interface losses of less than 1 dB (1.5 dB at bulkhead receptacle). Experimental results of fiber, cable, and cable assembly testing are reported.

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SUMMARY

The Ultra Low Loss contract was awarded to ITT Electro-Optical Products Division (EOPD) in Roanoke, Virginia on April 1, 1978. The purpose of the development funded under the contract was to develop fiber optic tactical cable assemblies with optical performance levels significantly better than previously available. The developed cable, prior to this contract, had characteristic attenuation of 20 dB/km and high dispersion due to its being step index. A graded-index fiber with attenuation <4 dB/km at $\lambda = 0.85\ \mu m$ and dispersion of <4 ns/km was developed - a helically laid cable design with good temperature performance to -55°C. The range of material properties still requires prescreening at cold temperature. Consequently, all delivered cables were tested at -55°C.

The cable developed consisted of six-fiber, helically wound fibers with polyurethane jacketing materials. The cable was subjected to mechanical testing to verify its ruggedness.

The connector development under this contract was by two companies: ITT Cannon Electric and Hughes Aircraft Company Connector Division. The ITT Cannon Electric Company connector did not meet the performance requirements, exhibited excess wear, and was dropped in favor of the Hughes connector. The Hughes connector is a true hermaphroditic connector with rugged connector body. The cable assembly was tested to verify the performance of the completed link. The finished cable assemblies showed typical connector loss in the 1.5 dB per mated pair range with no cold temperature contribution.

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1.0 INTRODUCTION

1.1 Contract Information

The Ultra Low Loss Cable Assembly program was awarded in 1978 to develop fiber optic tactical cable assemblies with optical performance levels significantly better than any available at that time. The system objective was the development of a fully tactical deployable cable which could support data transmission at 20 Mb/s over a repeaterless 8-km length of cable.

Contract DAAB07-78-C-2922 was awarded to ITT Electro-Optica Products Division (EOPD), in Roanoke, Virginia, on April 1, 1978, by the U.S. Army Communications Command, Center for Communication Systems (CENCOMS), Fort Monmouth, New Jersey.

1.2 Scope of Final Report

This final technical report describes the results of the work conducted under the contract from its award to its completion in December 1982. A copy of the technical guidelines followed in this development is included as Appendix C.

1.3 Background of Technical Problem

A previous optical fiber communication cable developed under contract DAAB07-73-C-0348 had characteristic attenuations of 20 dB/km at wavelengths in the region of λ = 0.60 mm to 1.06 mm. The fiber used was step-index and introduced high pulse dispersion due to the different optical paths traveled by the constituent modes. The fiber to be developed under this contract was to have low attenuation losses, and it was to achieve low dispersion by creating nearly equal optical paths for all optical modes.

1.4 Contract Technical Goals and Contract Deliverables

The goals established for the ultra low loss project were to develop the components necessary for a tactical, low loss cable:

- A fiber optic cable with attenuation of ≤ 5 dB/km at $\lambda = 850$ nm unaffected by temperature extremes and optical dispersion ≤ 1.5 ns/km
- A rugged cable design capable of withstanding the storage, shipping deployment, and environmental circumstances of tactical usage
- A connector with ≤ 1 dB/interface for cable interface connections and ≤ 1.5 dB/interface to the bulkhead mounted connector

The ultra low loss cable development effort was structured into four areas:

- Fiber configuration and materials evaluation
- Cable design development and evaluation
- Connector selection and testing
- Cable assembly procedures and evaluation

The success of each stage was monitored by delivery of successfully tested hardware. The deliverables fabricated by these evaluations were

- CLIN 0001 — Exploratory development cable
- CLIN 0002 — Three 300-m preliminary design cables
- CLIN 0003, 0004 — 12 pigtail assemblies, 6 with hermaphroditic connectors and 6 with bulkhead receptacles
- CLIN 0005 — Two 1-km and one 700 m cable assemblies (the third 1-km cable was found to have a fiber bubble at 700 m and was reterminated)

Regular accounts of the contract work were submitted in bimonthly and semi-annual reports. In addition, visualization data illustrating significant accomplishments and cable assembly drawings were supplied (CLIN 0006, 0007, 0008, and 0009).

1.5 ITT EOPD Development Plan

The following plan to develop the deliverable cable assemblies was created. The development of the cable with fiber and material selection was one task, and the connector and the assembly procedure was another task. Within the cable development task was the fiber and cable configuration development. The two development plans are included in Appendix A. The fiber development consisted of determining the fabrication method which produced the strongest fiber, dopants, and distribution necessary to meet the optical properties and configuration and jacket materials which best protected the fiber with minimum temperature sensitivity. The cable development resulted in the selection of materials and a configuration which met the tactical deployment problems of transportability, ruggedness, and weather resistance. The assembly development plan included the connector development and the cable to connector assembly procedures.

ITT Cannon Electric was actively involved in development of a fiber optic connector under ECOM contract DAAB07-76-Q-1357. ITT Cannon was contracted to provide the connectors for this contract in order to fully utilize the development efforts already underway.

Hughes Aircraft Company replaced ITT Cannon Electric as connector supplier in 1981 and the cable assemblies delivered to the Government used Hughes connectors installed by Hughes personnel.

A summary of the two development plans follows in Section 2.0.

Finally, prototype and finished cable assemblies were built and tested (CLIN 0003, 0004, and 0005).

2.0 ULTRA LOW LOSS DEVELOPMENT PLAN

The development was conducted in two stages. The cable development plan which included the fiber and cable configuration, is reviewed in paragraph 2.2 with the results presented in paragraph 3.1. The cable assembly development plan, which included the connector development and assembly procedures, is reviewed in paragraph 2.3 with the data presented in paragraph 3.2.

2.1 Development Plan Overview

The development goal of this contract was to provide a tactically deployable fiber optic cable as an alternate to presently used tactical communication cables. The communication systems constraints were

- 20 Mb/s transmission rate
- 8-km repeaterless links
- Tactical deployability under battlefield conditions

The optical performance goals determined to provide the system requirements included the following:

- Dispersion - <2 ns/km
- Attenuation - <5 dB/km at $\lambda = 0.85$ μm and connector interfaces <1 dB and <1.5 dB at bulkhead receptacle interfaces

The tactical field environment consists of a wide variety of terrains, climates, and weather conditions. The cable can be subjected to bending, twisting, pulling, abrasion, and crushing forces. The cable must resist degradation due to sunlight, chemicals and fuels, and biological organisms. Nuclear events can cause high ion field exposure, heat flash, and wind which the cable must withstand. Also, a need for rapid deployment and both hand and mechanical cleanability are required.

2.2 Cable Development Plan

The method of investigation followed in developing the individual components was to assign each task as a separate and parallel effort and to coordinate the developments for compatibility.

The cable development resulted in the selection of materials and a configuration which met the tactical deployment problems of transportability, ruggedness, and weather resistance.

2.2.1 Fiber Development Plan

The fiber development consisted of determining the fabrication method which produced the strongest fiber, dopants, and distribution necessary to meet the optical properties and configuration and jacket materials which best protected the fiber with minimum temperature sensitivity. The fiber fabrication method selected was a modified chemical vapor deposition (MCVD) inside a quartz tube. This method has two distinct advantages leading directly to the strength and graded-index goals of the contract:

- First, the high quality of the quartz tube provides a strong, uniform substrate. After drawing, the fiber is inherently stronger due to this feature.
- Second, the glass and dopants of the core can be easily controlled and modified to give a graded-index core profile for minimum dispersion.

The optimization of the fiber was accomplished by careful evaluation of the doping profile, its effect on the optical characteristics, the fiber draw, buffer applications, jacket extrusion, and the protective materials used, as well as the effect of each of these properties on the optical characteristics of the fiber.

2.2.1.1 Fiber Strength

Optical fibers employed in cables intended for field applications must be as strong as possible to withstand rough handling. Significant progress was made during the first year in the area of fiber strength improvement. Failure mechanisms were studied and fiber fabrication techniques were improved. Fibers were fabricated utilizing the improved techniques which exhibited significantly greater strength than earlier fibers. These fibers, tested continuously in greater than 1 km lengths, have withstood more than 3% strain without failure, and aging rate tests show that they will last for several years at 1% strain.

The achievements in fiber strength improvement were directly applicable to this proposed program; therefore, fibers fabricated for the 1 km cables with a minimum proof-test of 100 kpsi (1% strain) were used to minimize the possibility of fiber breakage in the field.

2.2.1.2 Fiber Dopants

Fiber dopants were used to achieve index grading by adding varying concentrations of dopant to the reactant gases as each deposition layer was added to the tube. Candidate dopants were germania, phosphorus, and boron.

At high doses, silicone cladded synthetic silica fibers are the most radiation resistant fibers presently available. These fibers show a saturation in the radiation induced losses at low radiation doses and an increase in radiation hardness after preirradiation without sacrificing the initial instrinsic optical losses in the near infrared.[1] Irradiation studies performed on Ge-doped silica fibers[2] showed similar behavior to that observed in high silica fibers. However, the Ge-doped silica fiber exhibited less radiation sensitivity at low doses and a faster rate of recovery compared to that observed in plastic clad silica fiber.[3]

Most, but not all, of the fibers prepared by ITT are doped with boron oxide in either the core or in the core and cladding. Boron is added to the cladding to lower the refractive index and increase the fiber's numerical aperture (NA). Boron addition lowers the fusion temperatures during the deposition of core and cladding and prevents premature collapsing. The boron dopant interacts with the thermal neutrons present in a mixed flux irradiation.

ITT has produced fibers with germania-silicate cores and silica cladding. However, such fibers are more expensive to produce than boron doped fibers. To reduce cost, phosphorous was added to lower deposition temperature. The use of phosphorous has a much lower reaction cross section with thermal neutrons as compared to that of boron and so will be less affected by radiation. ITT is currently producing fibers with phosphorous doping for some applications, so the production of such fibers does not present a problem. However, such fibers have a lower NA than germania-boron doped fibers.

2.2.1.3 Optical Properties

2.2.1.3.1 Attenuation

The development of the optical properties requires adjustment dopants and deposition to achieve grading and dimensional control; the quality of the process was controlled to achieve minimum losses.

2.2.1.3.2 Dispersion

Dispersion is the result of differing optical path lengths in the core. The grading of the refractive index of the layers of glass can be adjusted to make the optical path lengths of the higher order modes nearly equal to the low order optical path length. The dispersion goal was to reduce the dispersion to 2 ns/km or less.

2.3 Cable Assembly Development Plan

The cable/connector phase included the following steps:

- Evaluation of existing or planned connector design with respect to field repair, cable preparation requirements, cable strain relief mating characteristics, bulkhead mounting, and fiber removability
- Selection of preferred design and subcontractor
- Measurement of optical, mechanical, and environmental performance of prototype models

2.3.1 Connector Development Plan

The plan was to design a hermaphroditic connector which would terminate a six-fiber cable developed under this contract. The connector and cable design goal was to allow time division multiplexer (tdm) system transmission over eight 1-km links in tandem. The cable connector requirement was that it be hermaphroditic. The bulkhead receptacle requirement was also six-fiber with a capability to mate with the hermaphroditic connector. The tactical field environment imposed the requirements that the connector be rugged; easily cleaned; easily mated and unmated; coated with an environment-resisting, nonreflecting coating; and repairable.

The system operation was at selected wavelengths from $\lambda = 0.60$ to 1.06 μm with both analog and digital data transmission to 20 Mb/s/km. The hermaphroditic connector loss goal was 1.0 dB/km for plug-to-plug connection and 1.5 dB for plug-to-bulkhead receptacle connections.

This data further established the basis for the final connector evaluation established in the Connector Test Plan dated April 3, 1981, Doc Id No 81-12-10, which is shown in Appendix B.

Two connector manufacturers participated in this program. The first, selected at a joint meeting in Fort Monmouth, was ITT Cannon located in Santa Ana, California. In the kickoff meeting, which took place on November 17, 1978, it was mutually agreed by ITT EOPD and CECOM that ITT Cannon would pursue the adjustable three-sphere (ATS) connector approach, while the jeweled ferrule (JF) approach would be kept as a backup. However, ITT Cannon was terminated as connector subcontractor by ITT EOPD and CECOM in July 1981. The other supplier who became that final subcontractor for the connector design was Hughes Aircraft Co. in Irvine, California, which uses the precision contact design.

2.3.1.1 Connector Performance Objectives

The desired performance of a multichannel fiber optic connector can be described in three general categories. Optical performance objectives are related to the system loss budget which dictates the maximum allowable coupling loss. Mechanical parameters address the assembly, durability, and repair of the connectors. Environmental objectives seek to ensure operation under adverse dirt/water conditions.

A complete summary of the optical, mechanical, and environmental performance objectives is shown in Table 2.3.1.1-1.

The plan to select the best connector design to meet these goals was to conduct an industry search and to select the best design from those submitted. The selected manufacturer would then be subcontracted to provide the required connectors. Requests for proposal were sent to ITT Cannon, ITT Leeds, ITT Components (Europe), Hughes Aircraft Company, Deutsch, Cablewave, Amphenol, and AMP. After analysis of the responses, it was decided to take advantage of ongoing ITT Cannon development. The connectors by ITT Cannon did not perform as expected.

The connector plug and bulkhead receptacle design plan was delivered as CLIN 0007/A003(b), included as Appendix A.

Table 2.3.1.1-1. Connector Performance Objectives.

Optical

Plug-to-plug optical interconnection loss	$\leq$1 dB/km
Plug-to-receptacle optical interconnection loss	$\leq$1.5 dB/km
Crosstalk between adjacent fibers in the connector	-100 dB

Mechanical Installation

Coupling nut rotation	Coupling nut rotational torque $\leq$0.86 kg-cm
Mating durability	1000 mating/unmating cycles with <0.86 kg-cm coupling nut torque
Cable retention	181 kg tensile load without optical degradation
Cable flex life	2000 cycles room temp, 1000 cycles at -55°C with no optical degradation
Cable twist	1000 cycles behind connector with no optical degradation
Fiber removability	Provisions for insertion and removal of fibers from rear of connector
Mounting	Jam nut "D"-hole type panel mount
Field repair	Capable of repair by trained personnel in enclosed area
Cable preparation	Establish preparation procedure

Environmental

Salt spray	No mechanical degradation, no increase in optical loss

Table 2.3.1.1-1. Connector Performance Objectives (continued).

<u>Environmental (continued)</u>	
Immersion	1.8 m head of water for 24 h, no leaks
Shock drop	6 each, 3 m drops, no increase in optical loss
Sand and dust	No physical impairment, no increase in optical loss

2.3.2 Assembly Evaluation

The cable assembly evaluation proceeded through the following stages:

- Evaluation of cable/connector compatibility with NA, fiber tolerances, concentricity and roundness, fiber bend losses, strippability, cable strength member design, and cable jacket material
- Evaluation of fiber alignment techniques

Each of these design problems was evaluated by prototype fabrication and testing.

3.0 RESULTS

3.1 Cable Development Results

3.1.1 Fiber Development

The properties examined during the fiber optimization stage were fiber diameter, effect of NA, material hardness, strippability, effects of temperature cycling, and impact survivability.

Fibers offer immunity to electromagnetic interference (emi), radio frequency interference (rfi), and electromagnetic pulse (emp); however, while the fiber is relatively immune to emp from nuclear effects, it is subject to damage from the associated radiation. Radiation induced optical absorption and luminescence can cause temporary or permanent failure of the system. To evaluate the performance of the fibers developed, fibers manufactured for the Ultra Low Loss contract were required to undergo nuclear radiation exposure. In the past, observations indicated that optical attenuation increased dramatically during irradiation and for some time thereafter, showing various magnitudes of recovery directly dependent on the type and concentration of dopants used in the manufacturing process. This degradation of optical transmissivity was readily observed by utilizing simple electronic circuitry composed of a light emitting diode (LED) as the optical source and photovoltaic detectors to monitor the transmitted light. This is commonly known as a "throughput test" since the LED is merely biased into conduction and no modulating signal is imposed.

3.1.1.1 Configuration

To optimize producibility of the fiber and to best utilize existing connector designs, the core diameter was selected as 50 μm ±5 μm after initial samples of 55 μm had been produced. The optimization was achieved by close receiving inspection of materials such as quartz tubes and classification of the tubes to match them with the proper deposition to achieve final dimensional tolerances.

The fibers were silica glass performs with a graded-index deposition core. A fiber cross section and index profile is shown in Figure 3.1.1.1-1.

3.1.1.2 Dopants

Low loss optical fibers are currently produced by ITT using the internal MCVD process. The basic system consists of a chemical delivery system and a modified glass working lathe. The delivery system is a controlled reservoir for the ultrapure, high vapor pressure starting chemicals which constitute the basic chemical components of the desired glass composition. By finely controlling the flow of carrier gas through the liquid, a proper mixture of chemicals is delivered to the glass working lathe. The lathe is set up to support a substrate tube through which the chemicals can be passed. The glass of the desired composition formed by the vapor phase reaction in the delivery system is uniformly deposited

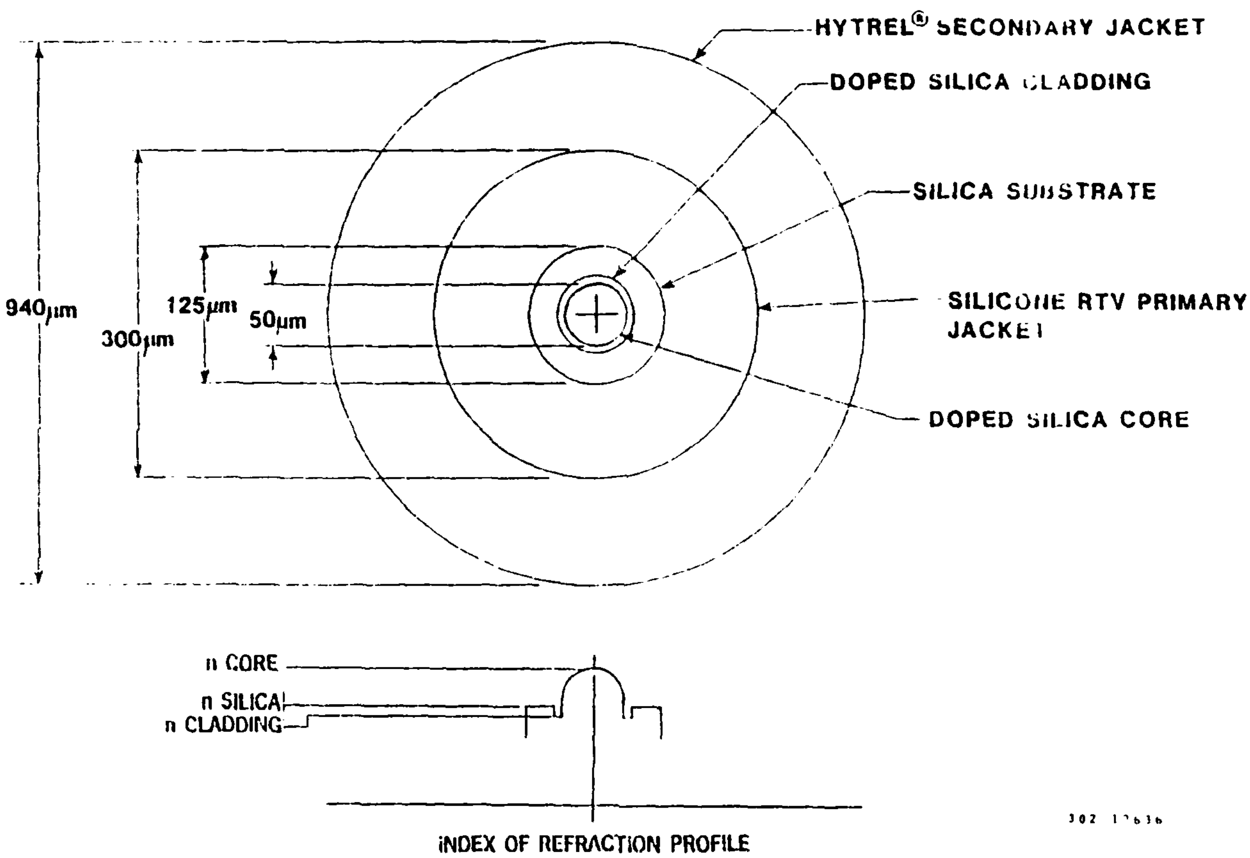


Figure 3.1.1.1-1. Wideband Graded-Index Multimode Optical Fiber.

in layers over the length of the internal surface of the substrate tube. The heat required to induce the chemical reaction is supplied by a traversing oxyhydrogen flame applied externally to the tube. After the glass deposition is completed, the flame temperature is raised to collapse the substrate into a solid preform. This preform is then prepared for fiber drawing.

The dopants used were varying amounts of phosphorus, boron, and germanium. The cladding is heavily boron doped (borosilicate), the phosphorus is almost constant across the profile, and the germanium is increased to the center of the core. The boron is used to reduce the refractive index. The germanium is used to increase the refractive index. The combination provides a continuously controllable profile with good controllability and strength.

3.1.1.3 Strength

The use of a tube as the outermost member of a fiber preform inherently offers high strength. For this reason, the MCVD method was chosen. The substrate tube quality has a large impact on the fiber strength characteristics along with the environment in which the preform is made and drawn. In order to maintain high strength, it is necessary to start with a substrate tube which is free from inclusions, trapped voids, or trapped gases. These defects can cause diameter fluctuation while drawing and weak spots within the glass structure which will cause fiber failure. Also, the surface quality of the preform can be greatly affected by the fabrication process itself. Foreign materials can be imbedded in the substrate tube's external surfaces by the traversing burner; therefore, it is important to maintain a clean environment throughout the whole fiber fabrication process.

3.1.1.3.1 Proof-Tester

The proof-tester provided an on-line 1% elongation proof-test which equals to a proof-stress level test of 690 N/mm^2 (100 kpsi) on the fiber by continuously applying tension to the fiber as it is spooled. Proof-testing of fibers is performed on-line as the fiber is drawn. The general design of the proof-tester is represented in Figure 3.1.1.3.1-1. The apparatus consists of two capstans with the second capstan controlled by a variable torque drive. By adjusting the torque applied to the second capstan, it is possible to vary the tensile load applied to the fiber to any desired level. The tensile load in the stressed portion of the fiber is measured, using an SAXL lever tension meter[10] Model L-20 which has been specially calibrated for use with optical fiber. A flexible belt prevents slippage of the fiber on the capstan.

3.1.1.3.2 Protective Measures

The fiber is protected from surface contaminates during the draw to enhance fiber strength by maintaining the pristine state of the fiber.

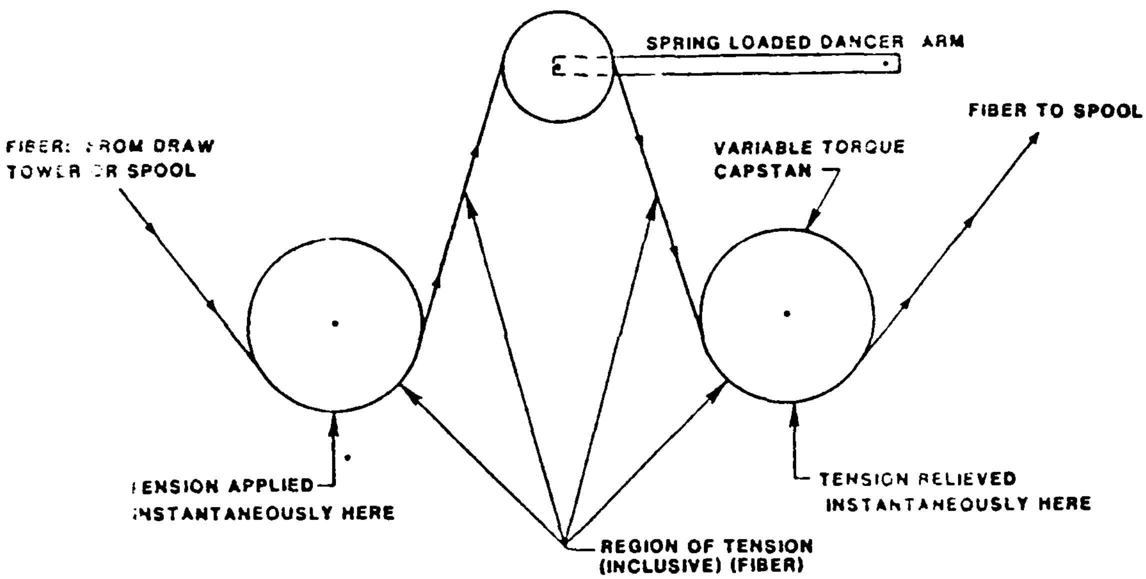


Figure 3.1.1.3.1-1. Proof-Testing Apparatus.

3.1.1.3.2.1 Clean Room Facility

The entire draw system is performed in a clean room kept clean and dust free (class 10,000). This maintains the strength of the fibers by preventing dust or moisture exposure to the raw glass.

3.1.1.3.2.2 Primary Coating

The primary coating material is Sylgard® 184 RTV silicone elastomer. The application of this buffer at the draw tower prevents moisture and airborne particles from adhering to the glass and causing weakness.

Silicone RTV was applied inline with a dipcoater to prevent degradation of fiber strength during fiber drawing. The dipcoater design facilitates self-centering of the silicone RTV coating around the fiber which reduces the probability of abrasion of the pristine fibers and therefore preserves fiber strength. After the coating has been applied, the coated fiber is passed through a curing furnace and is subsequently extruded with a Hytrel® jacket. This technique is employed by ITT EOPD on a routine basis for the fabrication of production fibers.

The soft silicone RTV was selected as primary coating to reduce bending and microbending losses. The silicone RTV coated fiber is then coated with a Hytrel® jacket to achieve the desired diameter. Jacket extrusion can be performed in tandem with the dipcoating process or separately during an off-line operation.

3.1.1.3.2.3 Furnace Purge Gas

A 50/50 mixture by volume of argon and helium gas is used to purge the furnace during the draw to provide a nonreactive atmosphere until the buffer is applied.

3.1.1.4 Fiber Diameter Effects

The fiber diameter effects were examined to determine the effect of core diameter with respect to throughput and fiber producibility. The diameter and concentricity of the core in the fiber control the match of the interfacing cores at the connector. Connector loss is a function of mismatches, as well as perpendicular end preparation.

Another mechanical characteristic important to connector loss is fiber dimensional control. To achieve connector losses less than 1 dB, fibers are drawn with a cladding diameter (125 μm) uniformity of ±2% or better. ITT has demonstrated that uniform fiber diameter can be achieved routinely without sacrificing fiber strength.

3.1.1.5 Jacket

To achieve a hard, flexible mechanical protection, Hytrel® was selected as the fiber jacket. Hytrel® polyester was selected for the jacket material because of its desirable characteristics at high and low temperature, high resiliency and flexibility, and its resistance to abrasion.

3.1.1.6 Fiber Temperature Attenuation Performance

A selection of fibers with diameters from 0.5 mm (0.020 in) to 1.14 mm (0.045 in) was evaluated at +10°C temperature intervals down to -65°C with constant attenuation monitoring. The attenuation data in Figures 3.1.1.6-1 and 3.1.1.6-2 indicates that the low temperature fiber performance with Hytrel® is dependant on buffer diameter. Fibers with buffer diameters to 0.99 mm (0.039 in) or less have significantly less attenuation than fibers 1.00 mm (0.040 in) in diameter or larger. The data also shows that fiber buffer diameters of 0.99 mm or less have a straight line curve to -65°C, but larger diameter fibers have a high attenuation increase point starting at approximately -35°C.

The sharp transition in attenuation increases above 1.0 mm finished outside diameter (od) can be attributed to linear compressive forces generated by the contracting fiber buffer reaching a level high enough to generate microbending of the glass fiber resulting in dramatically increased attenuation losses. Once buckling begins to occur, the bending losses increase rapidly.

The results of the low temperature attenuation testing on fibers indicate that to achieve optimum attenuation performance at low temperature (-55°C), the buffered fiber diameter must be 0.99 mm (0.039 in) or less to allow for manufacturing tolerances and always must remain below the knee in the curve shown in

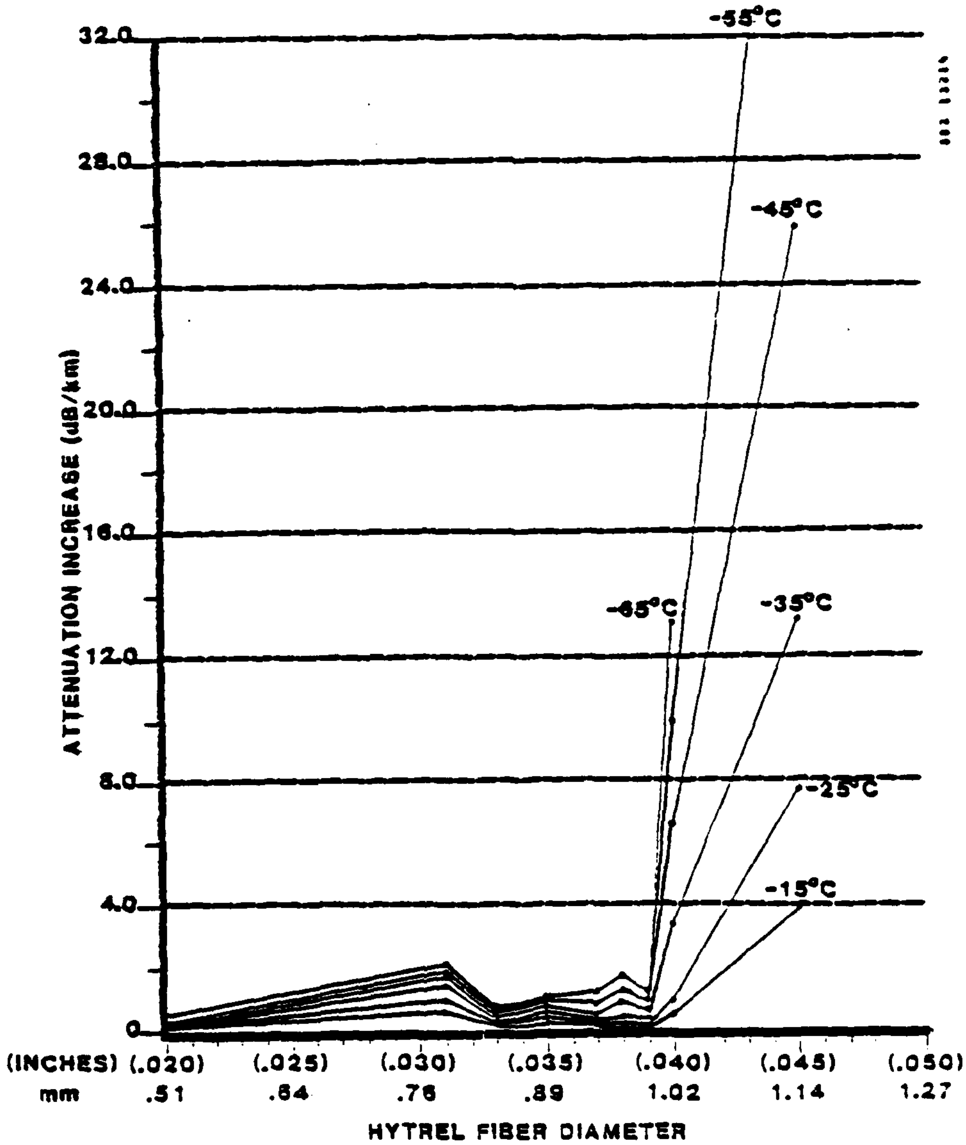


Figure 3.1.1.6-1. Low Temperature Attenuation Versus Fiber Diameter of Standard ITT Fibers.

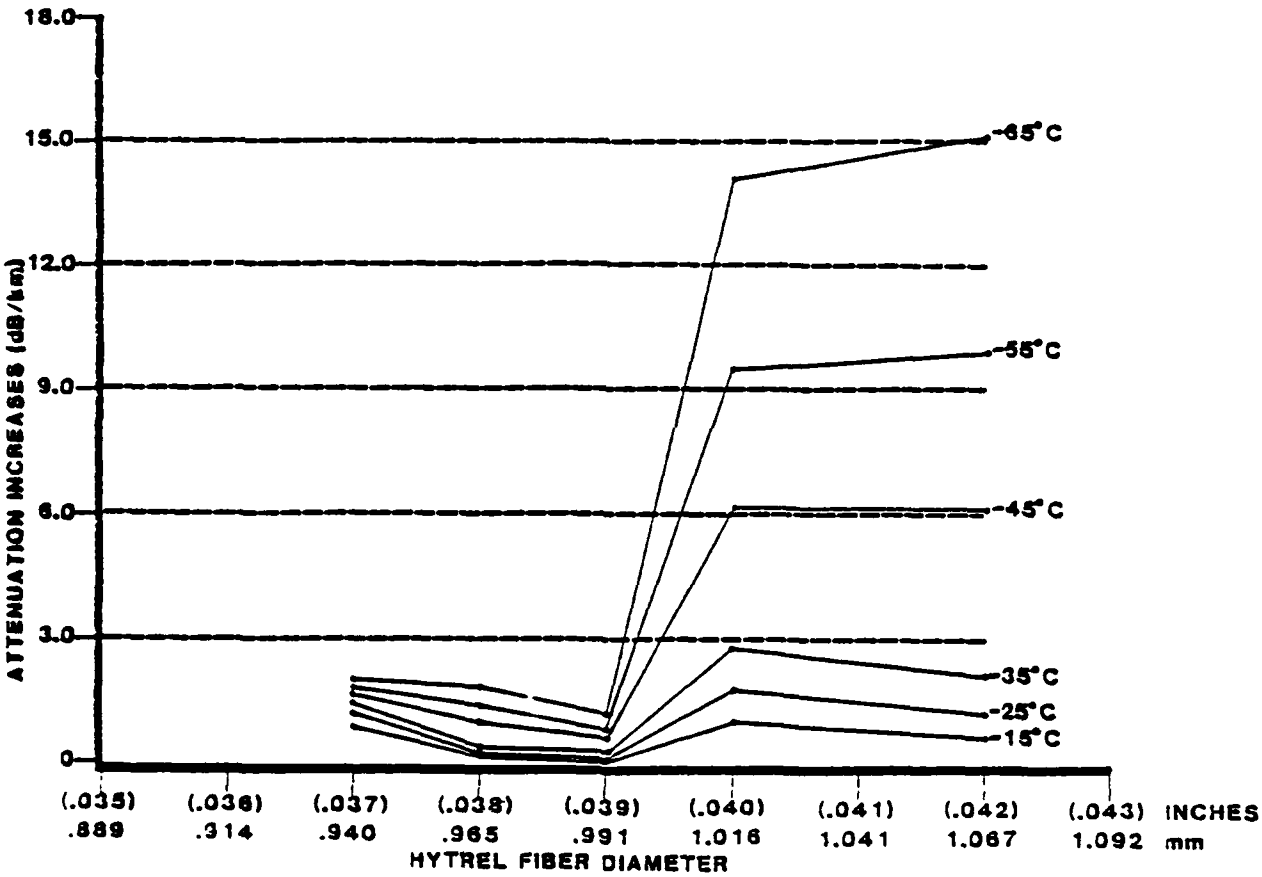


Figure 3.1.1.6-2. Low Temperature Attenuation Versus Fiber Diameter of Standard ITT Fibers (Second Sample).

Figure 3.1.1.6-2. This reduction in fiber buffer diameter results in reduced impact survivability.

3.1.1.7 Fiber Impact Survivability

A cable sample fabricated to the requirements of ultra low loss design 3 with 0.94 mm (0.037 in) diameter fibers was evaluated at various impact levels from 3.4 N•m to 6.0 N•m (2.5 to 4.5 ft•lb). The results shown in Figure 3.1.1.7-1 indicate that the fiber survivability drops off rapidly at levels greater than 4.0 N•m (3.0 ft•lb). The curve shows that at 3.4 N•m the cable withstands 1300 impact cycles without any fiber failures. The testing is further discussed in the Preliminary Design Model section.

At 1000 impact cycles, the fiber diameter for the final cable assemblies (0.94 mm ±0.05 mm (0.037 in ±0.002 in)) protects against impact load levels at 3.73 N•m (2.75 ft•lb). This provides for optimum impact resistance while maintaining excellent low temperature attenuation performance for the ultra low loss cable assemblies as shown in Figure 3.1.1.6-2.

3.1.2 Cable Assembly Development

The ultra low loss cable development centered on three preliminary cable designs which were submitted to CECOM as CLIN 0001. Three preliminary design models (PDM) and three exploratory design models (EDM) were developed and tested in this phase. A seventh

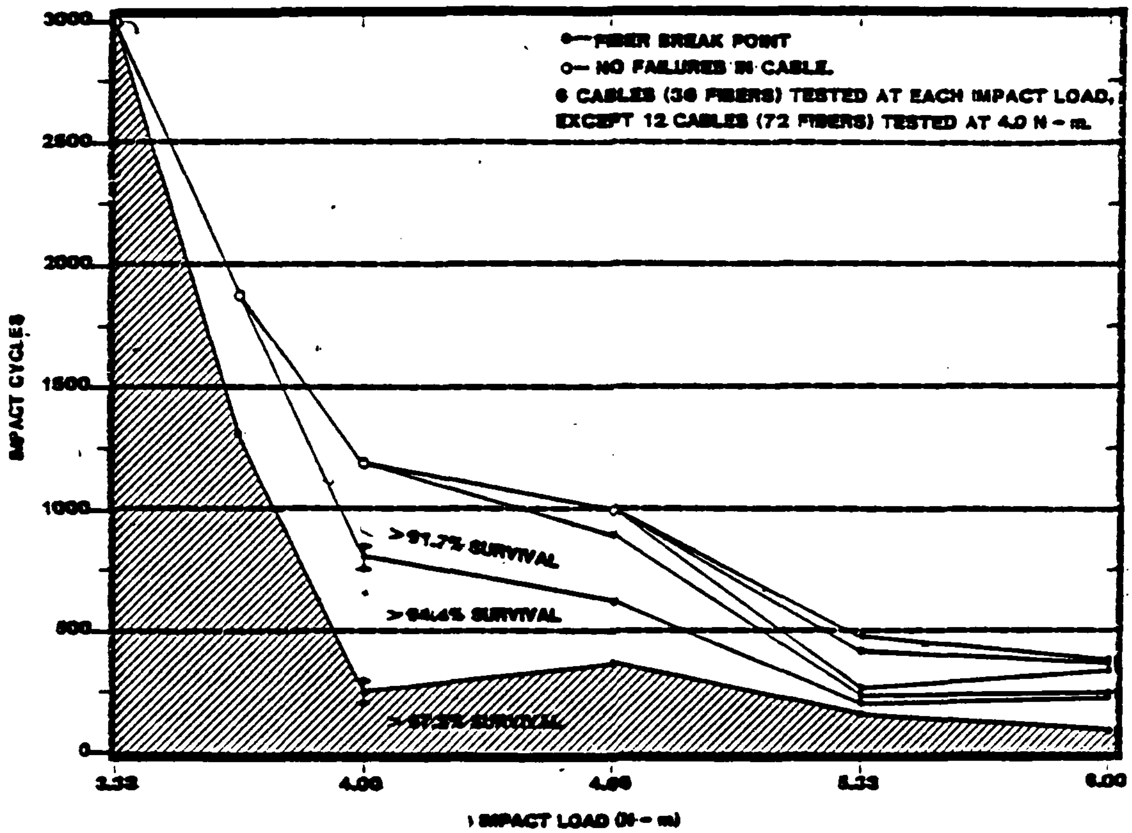


Figure 3.1.1.7-1. Impact Test (Room Temperature) Ultra Low Loss Cable Design 3 With 0.94 mm (0.037 in) Fibers.

model with polyurethane jacketed fiber was also fabricated as part of the fiber jacket evaluation. This development effort is described in the following paragraphs.

3.1.2.1 Exploratory Development Models (EDM)

This subsection covers the description, construction, and evaluation of the EDM cable samples.

An EDM cable test plan was submitted and approved for this phase and is included in Appendix A of this report.

3.1.2.1.1 EDM Cable Designs

The three cable samples were fabricated in accordance with the cable design plan. The EDM cable samples were fabricated using Uniroyal Roylar® E-80 polyurethane for the jacket layers because of its better low temperature flexibility.

3.1.2.1.1.1 Center Member Design

For evaluation, three center filler elements were varied in the three designs as follows:

- Design 1 - Optical fiber
- Design 2 - Nylon monofilament
- Design 3 - Polyurethane (E-80) coated Kevlar® 49 (380 denier)

Cable design 1 was not selected since it would require an extra optical fiber.

Cable design 2 requires a nonoriented nylon monofilament as the central element. Since it is difficult to define the degree of orientation acceptable, it was not selected. Therefore, cable design 3 was the best alternative.

3.1.2.1.2 Optical Fibers

All the optical fibers used in these cables are specifically fabricated for the program. The fibers were manufactured between November 1978 and February 1979. The fibers were buffered to 1.02-mm diameter with Hytrel® 7246. All EDM fibers were measured while strung between two drums with a centerline distance of 10 m. This evaluation procedure eliminates spooling losses and is a true measure of the intrinsic attenuation. The dimensional measurements for all fibers are listed in Table 3.1.2.1.2-1.

3.1.2.1.3 Temperature Sensitivity

It was found that the fibers were sensitive to low temperature, which greatly increased the optical attenuation of the cabled fibers. This was an unexpected problem because a number of cables (designed for commercial telecommunication applications) had been tested at low temperature (-40°C and -50°C) with loss increases from 1 to 1.5 dB/km.

Table 3.1.2.1.2-1. Dimensional Measurements of EDM Cable Samples.

	Core Diameter (μm)		Cladding Diameter (μm)	
Design 1	SOP*	EOP**	SOP*	EOP**
Center	57 x 61	63 x 67	122	135
1) Yellow	57 x 60	57 x 59	127	131
2) Orange	59	59	127	129
3) White	58	59	127	129
4) White	54	50	125	123
5) White	53 x 57	56 x 57	125 x 129	127
6) White	64 x 67	56 x 59	140	125
Design 2				
1) Yellow	53 x 55	56	125	129
2) Orange	56	56	125	125
3) White	57	59 x 56	122 x 127	125
4) White	60 x 61	57 x 59	125 x 129	127 x 129
5) White	52 x 54	57 x 60	122 x 125	119 x 125
6) White	53 x 56	53 x 55	125	127
Design 3				
1) Yellow	56	56 x 58	123 x 125	125
2) Orange	58 x 61	61	123	127
3) White	59	59	125 x 127	127 x 129
4) White	60 x 61	59 x 61	119	125 x 127
5) White	61	62	123	127 x 129
6) White	60 x 61	59	125	127 x 129

*Start of pull, bottom of spool.
**End of pull, top of spool.
***The above fibers were drawn to meet the dimensional requirement of that time i.e., 55 ±5 μm.

These cables were fabricated using some of the same batch fibers as previously used, with similar results noted at low temperatures. At this point, it was suspected that the problem might be a fiber problem and not due to the cable design. Therefore, several fibers fabricated for the ultra low loss contract and a few fibers from the regular production inventory were exposed to low temperatures. The results and conclusions are reported in paragraph 3.1.1.6. The data showed that 0.94 ±0.05 mm (0.037 ±0.002 in) was the optimum fiber diameter.

Figures 3.1.2.1.3-1, 3.1.2.1.3-2, and 3.1.2.1.3-3 depict the performance of the fibers of the EDM cables when exposed to temperatures from -65°C to +65°C. Fiber identification was not recorded during the test.

Two cables were designed to incorporate features of the telecommunication cables. These are shown in Figures 3.1.2.1.3-4 and 3.1.2.1.3-5 and were labeled designs 4 and 5, respectively.

Tables 3.1.2.1.3-1 through 3.1.2.1.3-3 summarize the performance of the EDM cables before and after environmental testing. Attenuation at each wavelength was measured with 0.089 injection NA. The average excess cabling loss at 8200 Å was:

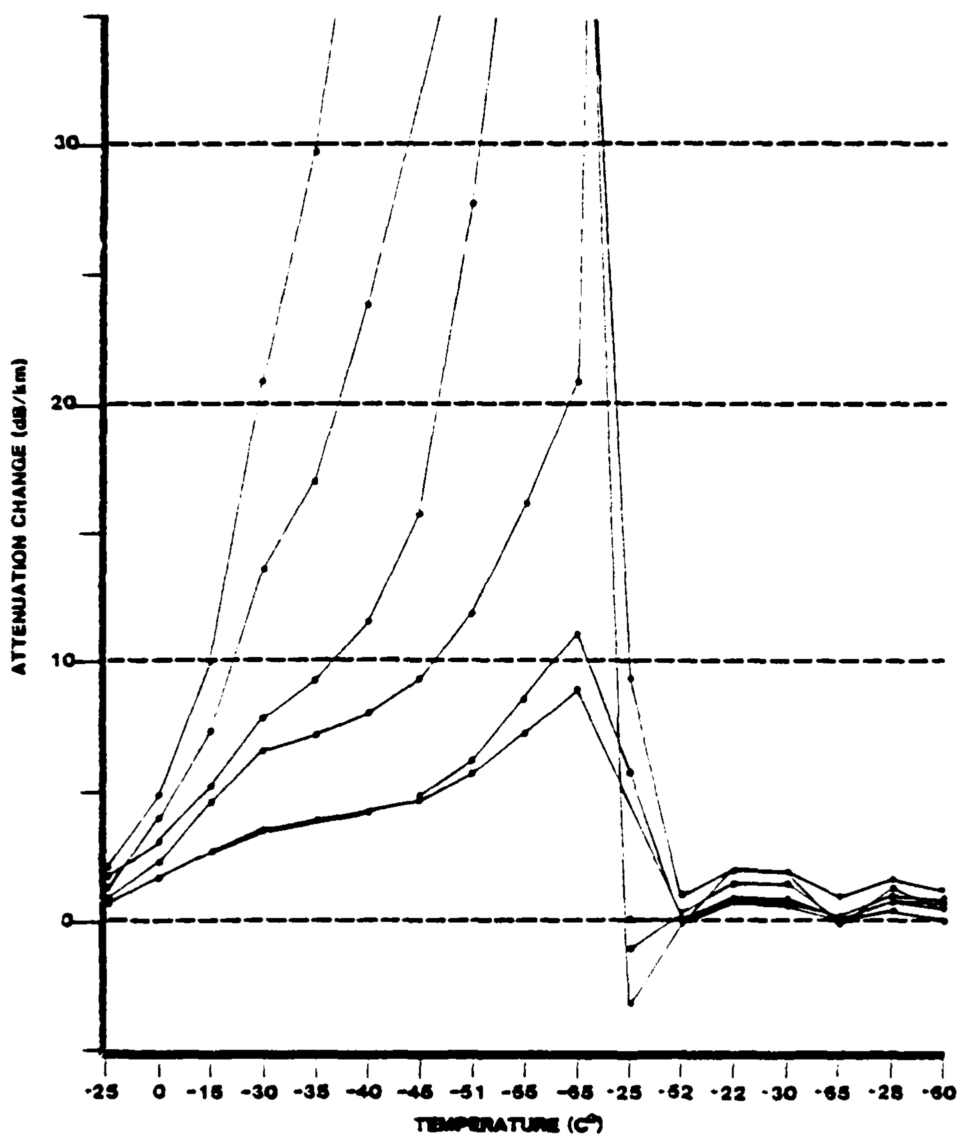


Figure 3.1.2.1.3-1. Design 1 - Ultra Low Loss Fib… Optic Cable. Individual Fiber Performance Over Temperature Test of the Cable.

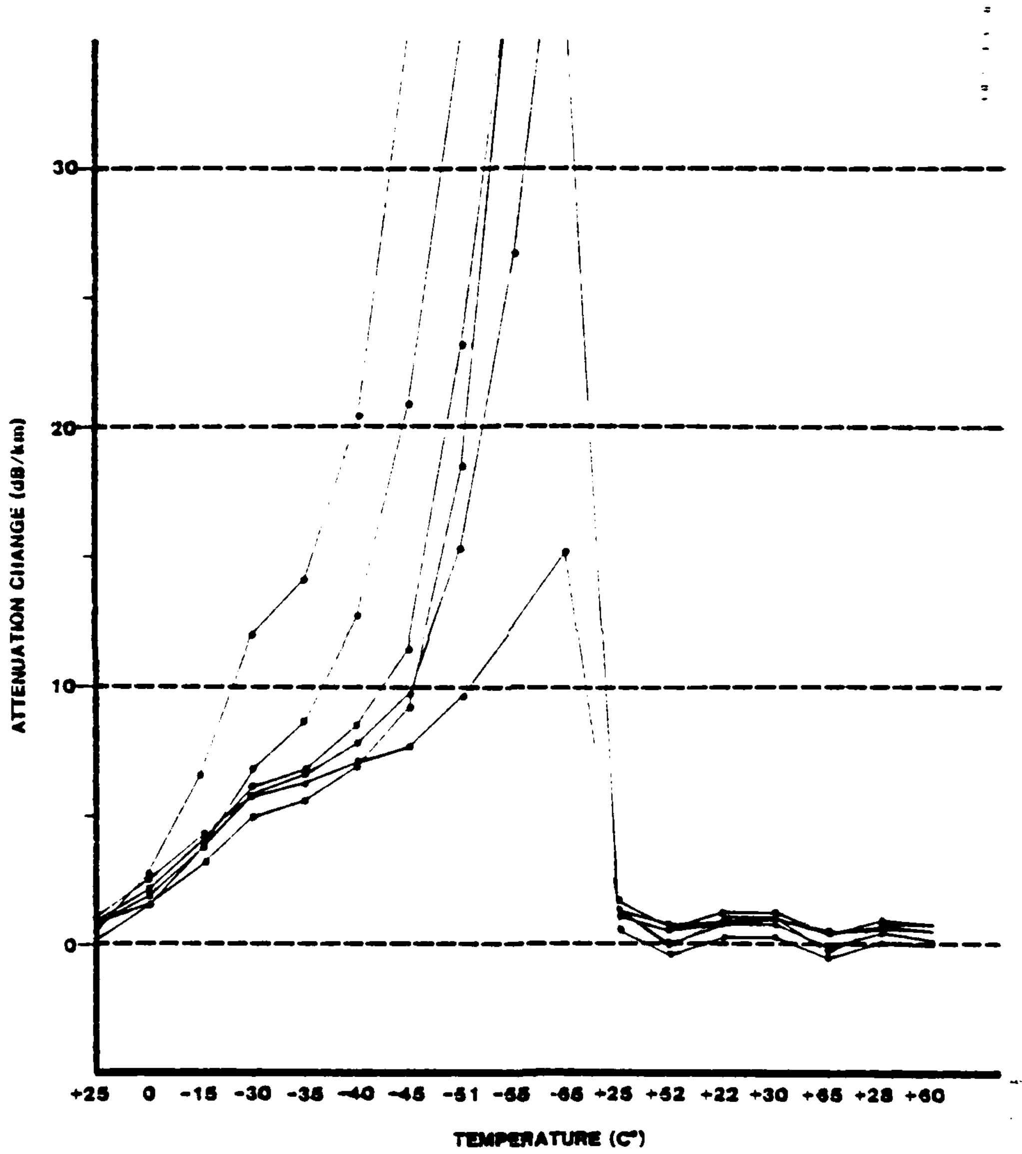


Figure 3.1.2.1.3-2. Design 2 - Ultra Low Loss Fiber Optic Cable. Individual Fiber Performance Over Temperature Test of the Cable.

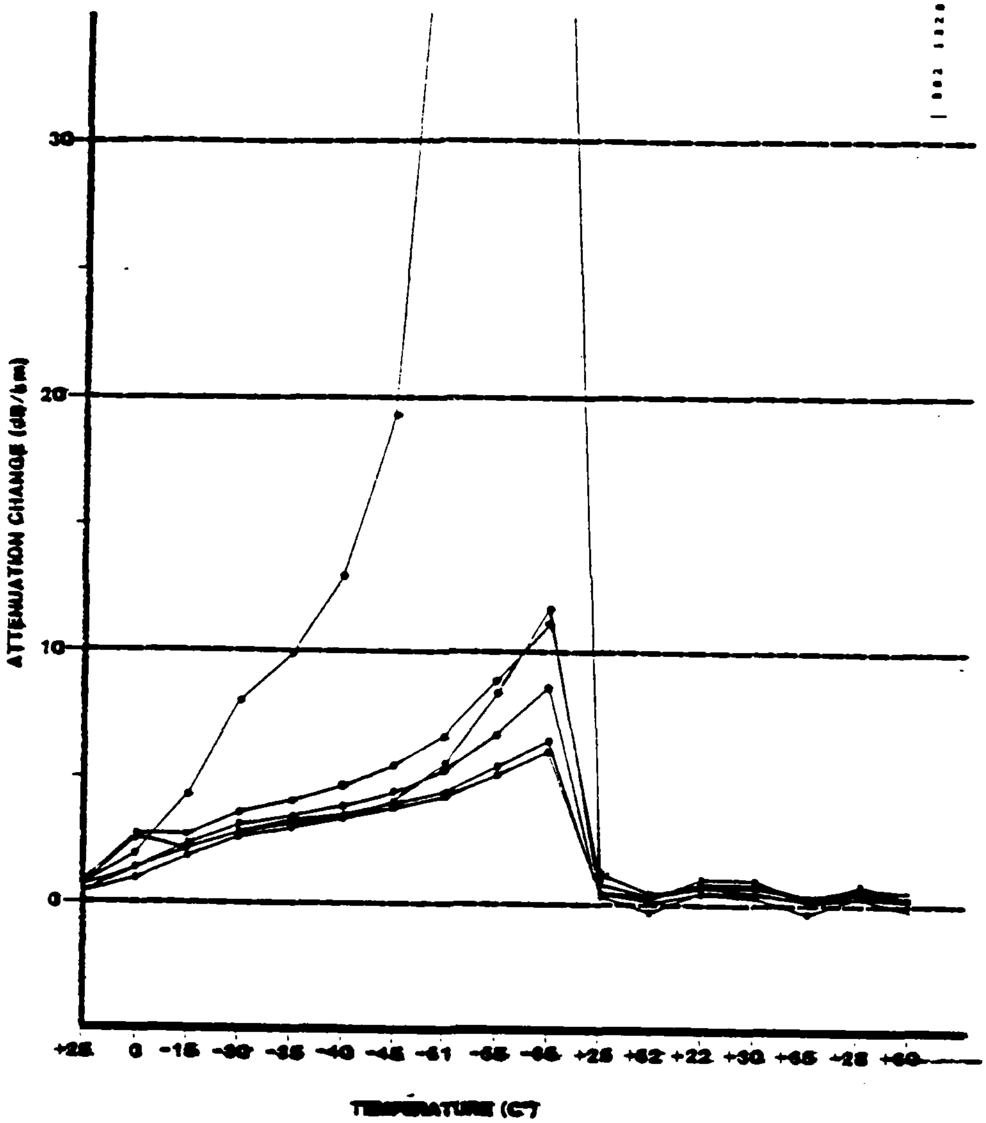


Figure 3.1.2.1.3-3. Design 3 - Ultra Low Loss Fiber Optic Cable. Individual Fiber Performance Over Temperature Test of the Cable.

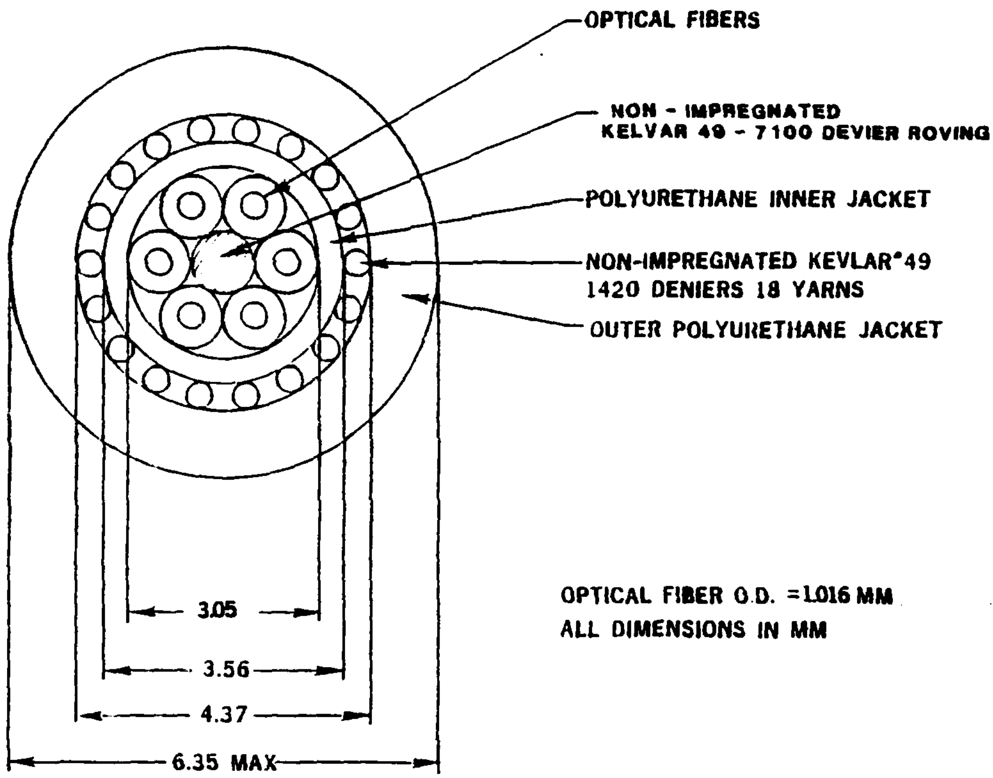


Figure 3.1.2.1.3-4. Design 4 - Ultra Low Loss Fiber Optic Cable.

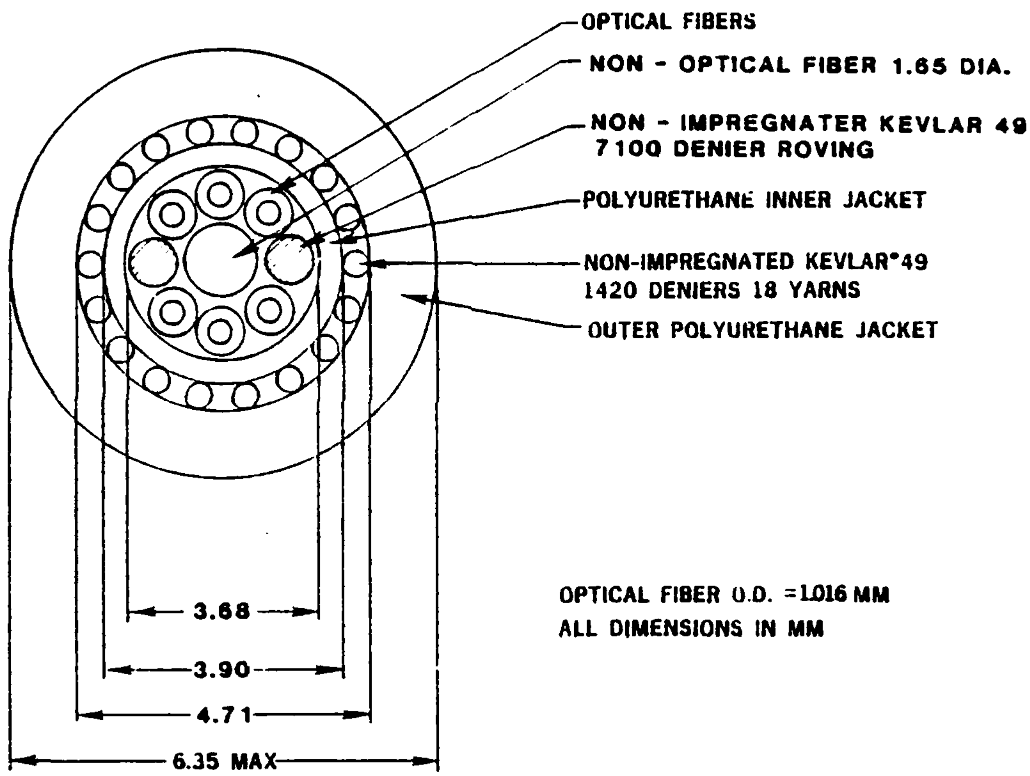


Figure 3.1.2.1.3-5. Design 5 - Ultra Low Loss Fiber Optic Cable.

Table 3.1.2.1.3-1. Attenuation of Cable Design 1 Before and After Environmental Testing (dB/km).

	Fiber #1 (Yellow)				Fiber #2 (Orange)				Fiber #3			
Wavelength (μm)	.82	.85	1.05	1.09	.82	.85	1.05	1.09	.82	.85	1.05	1.09
Original Evaluation After Cut to Length (658 m)	3.62	3.30	1.68	1.62	3.48	3.27	1.55	1.31	4.13	3.66	2.10	2.32
After Temperature/humidity Test	4.08	-	-	-	4.20	-	-	-	5.08	-	-	-
After Temperature Shock Test	3.67	3.13	1.25	1.47	4.19	3.70	1.88	1.98	5.19	4.52	2.79	2.76
After Vibration Test	4.24	3.67	2.15	1.07	4.21	3.75	2.10	1.55	4.87	4.26	2.71	2.53
Δ Attenuation (Original vs Final)	.62	.37	.47	.55	.73	.48	.55	.24	.74	.60	.61	.21

	Fiber #4				Fiber #5				Fiber #6			
Wavelength (μm)	.82	.85	1.05	1.09	.82	.85	1.05	1.09	.82	.85	1.05	1.09
Original Evaluation After Cut to Length (658 m)	4.01	3.60	1.91	1.89	4.61	4.04	2.67	2.54	5.51	4.47	2.78	2.83
After Temperature/humidity Test	5.14	-	-	-	5.52	-	-	-	5.84	-	-	-
After Temperature Shock Test	5.10	4.66	3.29	2.83	5.40	4.76	3.13	3.05	5.69	5.07	2.98	2.88
After Vibration Test	5.55	4.95	3.38	2.93	5.74	5.10	3.72	3.21	5.55	4.95	3.38	2.93
Δ Attenuation (Original vs Final)	1.54	1.35	1.47	1.04	1.13	1.06	1.05	.67	.04	.48	.60	.10

Table 3.1.2.1.3-2. Attenuation of Cable Design 2 Before and After Environmental Testing (dB/km).

	Fiber #1 (Yellow)				Fiber #2 (Orange)				Fiber #3			
Wavelength (μm)	.82	.85	1.05	1.09	.82	.85	1.05	1.09	.82	.85	1.05	1.09
Original Evaluation After Cut to Length (678 m)	5.35	4.66	3.58	3.44	4.14	3.58	2.22	2.13	5.05	4.42	2.22	2.10
After Temperature/humidity Test	6.00	-	-	-	5.48	-	-	-	5.62	-	-	-
After Temperature Shock Test	6.68	6.33	5.10	4.85	4.66	4.34	2.88	2.78	5.44	4.64	1.95	2.20
After Vibration Test	7.05	6.75	5.45	5.06	5.21	4.80	3.21	2.84	5.54	4.91	2.87	2.42
Δ Attenuation (Original vs Final)	1.70	2.09	1.87	1.62	1.07	1.22	.99	.71	.49	.49	.65	.20

	Fiber #4				Fiber #5				Fiber #6			
Wavelength (μm)	.82	.85	1.05	1.09	.82	.85	1.05	1.09	.82	.85	1.05	1.09
Original Evaluation After Cut to Length (678 m)	3.68	3.47	1.48	1.43	4.34	4.01	2.44	2.25	4.79	4.21	2.87	2.81
After Temperature/humidity Test	3.84	-	-	-	5.24	-	-	-	5.64	-	-	-
After Temperature Shock Test	3.98	3.41	2.05	1.85	4.57	4.02	2.52	2.30	5.72	5.13	3.58	3.52
After Vibration Test	3.89	3.42	1.91	1.78	5.09	4.60	2.87	2.76	6.18	5.60	4.28	3.77
Δ Attenuation (Original vs Final)	.21	-.05	.43	.35	.74	.59	.43	.51	1.39	1.39	1.41	.96

Table 3.1.2.1.3-3. Attenuation of Cable Design 3 Before and After Environmental Testing (dB/km).

	Fiber #1 (Yellow)				Fiber #2 (Orange)				Fiber #3			
Wavelength (μm)	.82	.85	1.05	1.09	.82	.85	1.05	1.09	.82	.85	1.05	1.09
Original Evaluation After Cut to Length (666 m)	5.24	4.49	3.07	3.52	3.84	3.29	1.85	1.82	4.49	4.41	2.39	2.23
After Temperature/humidity Test	5.63	-	-	-	4.51	-	-	-	5.57	-	-	-
After Temperature Shock Test	4.98	4.30	2.97	2.66	4.41		2.62	2.36	4.66	4.44	2.68	2.46
After Vibration Test	5.15	4.65	2.98	3.01	5.16	4.52	2.72	2.40	5.03	4.51	3.00	2.90
Δ Attenuation (Original vs Final)	-.09	.16	-.09	-.051	1.32	1.23	.87	.58	.54	.10	.61	.67

	Fiber #4				Fiber #5				Fiber #6			
Wavelength (μm)	.82	.85	1.05	1.09	.82	.85	1.05	1.09	.82	.85	1.05	1.09
Original Evaluation After Cut to Length (666 m)	4.36	3.77	2.28	2.16	4.50	3.79	2.53	2.39	4.55	3.68	2.35	2.24
After Temperature/humidity Test	5.55	-	-	-	4.96	-	-	-	5.58	-	-	-
After Temperature Shock Test	5.22	4.73	2.90	3.02	5.18	4.20	2.39	2.55	5.51	4.74	3.32	3.16
After Vibration Test	5.85	5.48	3.81	3.76	5.03	4.54	2.92	2.92	5.92	5.50	3.71	3.25
Δ Attenuation (Original vs Final)	1.49	1.77	1.53	1.60	.53	.75	.39	.53	1.37	1.82	1.36	1.01

- Cable design 1 - 0.54 dB/km
- Cable design 2 - 0.49 dB/km
- Cable design 3 - 0.51 dB/km

All were workable design values.

3.1.2.1.4 Fungus Test

This test was performed by Aerospace Research Corporation. The test procedure consists of exposing a sample of cable to a fungus culture as detailed ultra low loss cable assembly guidelines (paragraph 3.2.3.2.6) in Appendix C. The test report indicated that there was a very light growth on the surface of all six cables. These samples were returned to ITT EOPD where this light growth was verified by observation under the microscope. A very light surface film of processing lubricant was responsible for a small amount of fungus growth. The cable material was not attacked and the cable performance was not degraded.

3.1.2.1.5 Polyurethane Jacket Evaluation

The three 1 km cables and a 300 m length of cable for bulkhead receptacle terminations were processed through the cabling operation and stopped because of a Roylar® E-9B polyurethane while performing satisfactorily at room temperature exhibited a low temperature problem. This problem resulted in circumferential cracks around the jacket while the cable was subjected to bend testing around a sheave at low temperature, indicating brittleness at -54°C. A sample cable was fabricated and mechanical evaluations conducted to determine if the new Roylar® E-9BE polyurethane was acceptable. Uniroyal made a formulation change on the grade of polyurethane and indicated that there would be no performance variation from previous batches. In fact, the samples ITT EOPD evaluated indicated a low temperature brittleness with severe jacket cracking. During this time frame, the polyurethane manufacturing facilities and all rights were sold by Uniroyal to B.F. Goodrich.

3.1.3 Preliminary Design Model (PDM)

This subsection covers the description, contruction, and evaluation of the three PDM cable samples delivered.

3.1.3.1 Optical Fibers

The light transmitting elements of the cable are the graded-index optical fibers (Figure 3.1.1.1-1) consisting of a glass core (germanium, phosphorus, and boron dopants) and a glass cladding (germanium, phosphorus, and boron dopants) developed in the exploratory development models.

3.1.3.1.1 Optical Properties

The graded-index optical fibers were to meet the following specifications at 0.82-μm wavelength after proof loading at 100,000 psi: (1% elongation)

- Fiber core: 56 μm ±5 μm
- Fiber od: 125 μm ±6 μm
- Attenuation: ≤5.0 dB/km
- Dispersion: ≤2.0 ns/km
- NA (90% power): ≥0.14

The attenuation and dispersion of the three preliminary design models were measured with results indicated in Table 3.1.3.1.1-1. The values were higher than the 5.0 dB/km attenuation and the 2.0 ns/km dispersion guidelines established for this program. The purpose of the exploratory design models was to examine various cable geometries and not to strive for best optical characteristics. The optical performance was further addressed in the exploratory development models. The attenuation measurement error due to injection conditions was multiplied on short length samples with error deviation uncertainty. A description of the attenuation and dispersion measurement technique is located in Appendixes A and B.

All three preliminary design models were shipped after completing the optical evaluation.

3.1.3.2 Center Member

The center filler element of the cable was varied in the three designs as follows:

Table 3.1.3.1.1-1. Optical Characteristics of Preliminary Design Models.

Design	Fiber	Attenuation at 0.85 μm (dB/km)	Dispersion at 0.9 (ns/km)
	1	6.22	2.09
1	2	6.33	1.53
(303 m)	3	6.05	2.92
	4	7.31	2.79
	5	6.56	1.53
	6	9.61	4.73
	7	7.29	2.32
2	1	6.11	2.38
(353 m)	2	5.99	3.52
	3	6.56	2.07
	4	5.49	1.31
	5	5.59	1.17
	6	6.39	3.42
3	1	8.35	2.04
(275 m)	2	7.98	2.01
	3	8.38	2.71
	4	8.98	2.10
	5	9.83	2.44
	6	9.05	1.61

- Design 1 - Optical fiber
- Design 2 - Nylon monofilament
- Design 3 - Polyurethane coated Kevlar® 49 (380 denier)

Design 3 center filler provides a cushioning effect, improving impact resistance.

3.1.3.3 Polyurethane Inner Jacket

The polyurethane inner jacket was extruded after the fiber stranding operation. The polyurethane used was Roylar® E9-B, a polyether based compound manufactured by Uniroyal. It was chosen because of its extreme toughness, abrasion resistance, low temperature flexibility, resistance to hydrolysis, fungus resistance, and excellent stability to atmospheric conditions. This jacket supplied support for the fiber making up the cable core and provided a buffer layer between the fiber and Kevlar® thereby reducing abrasion.

3.1.3.4 Kevlar® Strength Member

Kevlar® 49 was chosen as the strength member for this application because of its strength versus weight properties and durability. A total of 18 yarns (1420 denier) was applied helically with a 10.1 cm (4.0 in) lay length. The lay length was selected to be greater than that of the fibers to ensure that the Kevlar® takes the tensile load. The strength member provided 181.8 kg (400 lb) tensile strength at 1% elongation. One percent elongation was the 100 kpsi fiber proof-test level.

3.1.3.5 Polyurethane Outer Jacket

The outer jacket material was identical to the inner jacket. Figures 3.1.3.5-1 through 3.1.3.5-3 show the cable construction for the three preliminary design models.

3.1.3.6 Preliminary Design Model Tests

3.1.3.6.1 Transmission Tests

3.1.3.6.1.1 Attenuation

3.1.3.6.1.1.1 Specification

The specifications were

- Wavelengths: 8,200, 8,500, and 10,500 Å
- Attenuation: 5 dB/km maximum
- Other wavelengths: 12,000, 13,000, and 14,000 Å (data obtained for information only)

Table 3.1.3.6.1.1.1-1 shows the attenuation of each fiber of cable designs 1, 2, and 3 at 8200 Å with an injection NA of 0.089. Note that this table gives the attenuation of each fiber before and after cabling. The attenuation of the fiber before cabling was measured while it was strung between two drums (10 m from center to center). The purpose of stringing the fibers is to eliminate the spooling loss due to crossovers and tension from the true

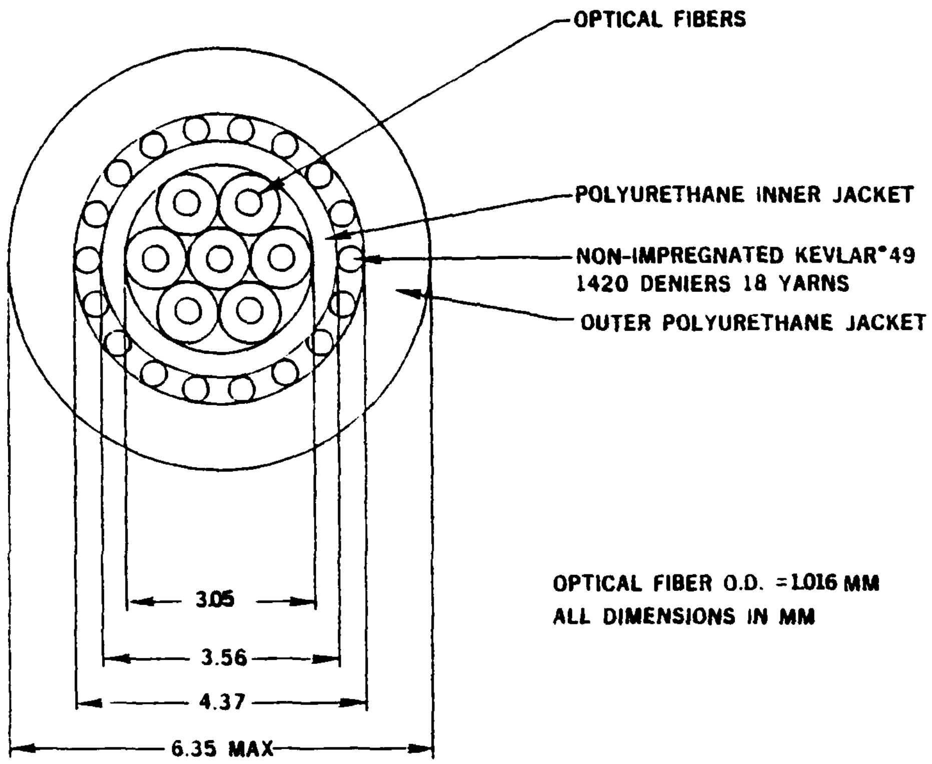


Figure 3.1.3.5-1. Design 1 - Ultra Low Loss Fiber Optic Cable.

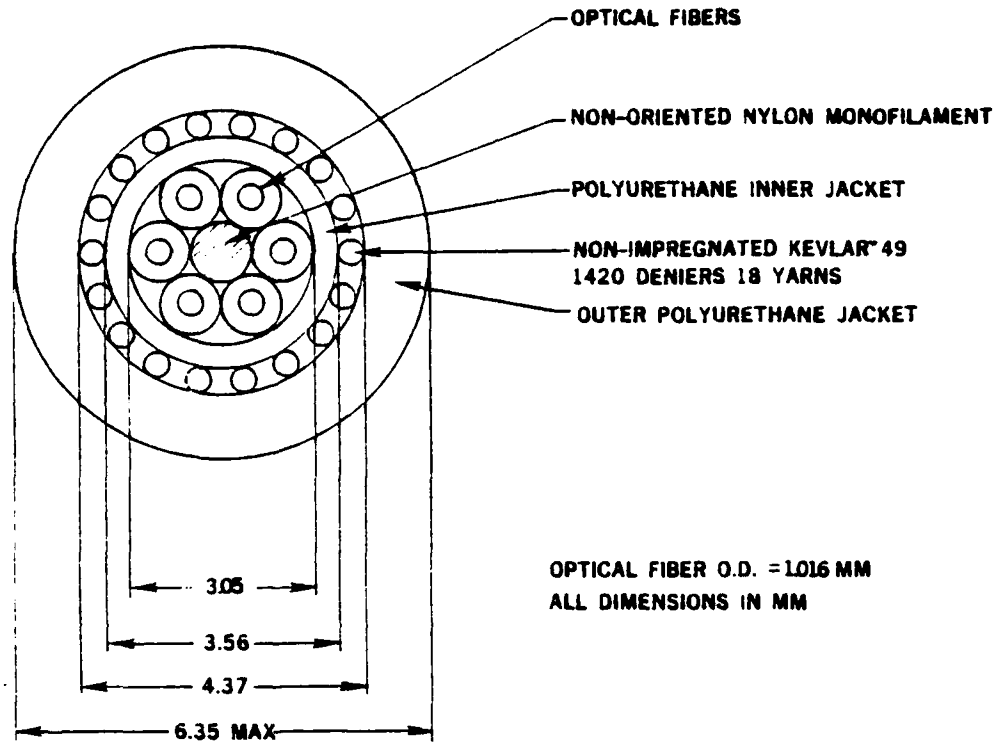


Figure 3.1.3.5-2. Design 2 - Ultra Low Loss Fiber Optic Cable.

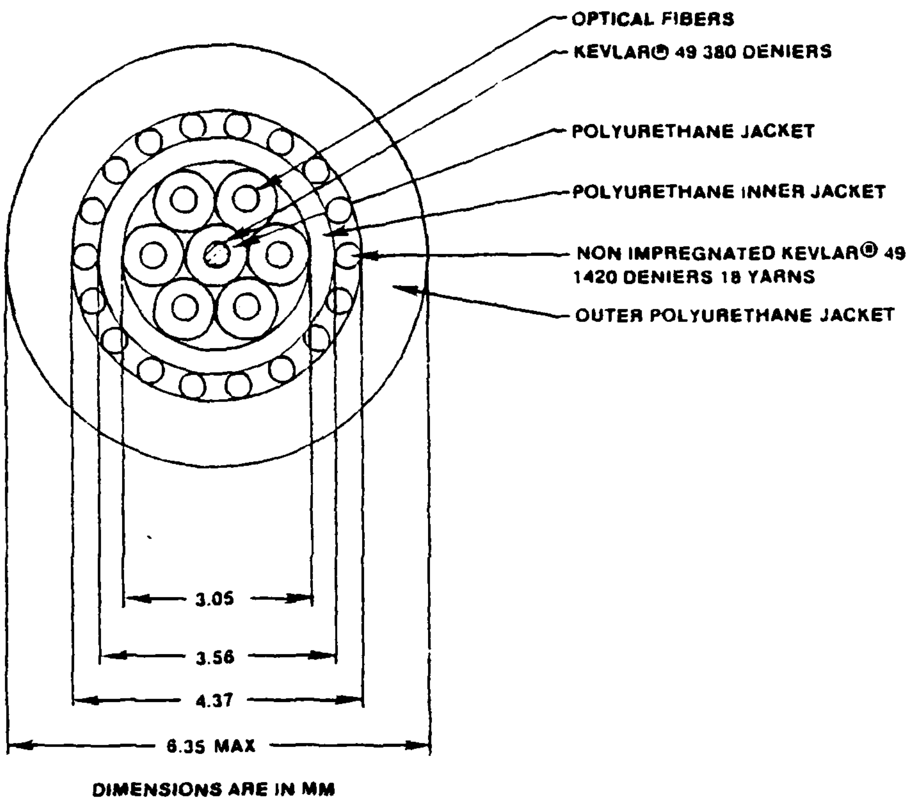


Figure 3.1.3.5-3. Design 3 - Ultra Low Loss Fiber Optic Cable.

Table 3.1.3.6.1.1.1-1. Attenuation (dB/km) at 0.82 μm of Ultra Low Loss Cables.

	Cable Number								
	020979 MA II (Design 1)			022679 MA II (Design 2)			030279 MA II (Design 3)		
Fiber No	Before*	After**	Δα	Before*	After**	Δα	Before*	After**	Δα
Center	4.27	4.80	+0.53	-	-	-	-	-	-
1	3.59	3.91	+0.32	3.76	4.77	+1.01	4.24	5.04	+0.80
2	3.75	3.70	-0.05	3.44	3.97	+0.53	3.54	3.92	+0.38
3	3.65	4.04	+0.39	4.62	5.12	+0.50	3.86	4.33	+0.47
4	3.52	3.98	+0.46	3.57	3.68	+0.11	4.22	4.22	+0.00
5	3.66	4.81	+1.15	4.29	4.39	+0.10	3.98	4.26	+0.28
6	4.14	5.15	+1.01	3.56	4.24	+0.68	3.24	4.80	+1.56
Average (dB/km)***	3.80	4.34	+0.56	3.87	4.36	+0.49	3.85	4.43	+0.57
Center element	Fiber			Nylon monofilament			Polyurethane jacketed Kevlar®		

Average attenuation increase of all fibers (dB/km) - +0.50

*Attenuation of strung fiber.
**Attenuation of cabled fiber.
***Includes center fiber.

attenuation of the fiber. This procedure allows the excess cabling loss to be determined more accurately.

Table 3.1.3.6.1.1.1-2 shows the performance of cable designs 1, 2, and 3 when measured at 8,200; 8,500; 10,500; 10,900; 11,000; 12,000; 13,000; and 14,000 Å (0.089 injection NA). With the exception of one fiber (at 8200 Å) which barely misses the goal of 5 dB/km, each cable design met the contract goal at the wavelengths from 8,200 to 13,000 Å. The best performance was found at 12,000 Å.

The contract does not require meeting the 5 dB/km goal at 14,000 Å. This wavelength is affected by a water peak, but since significant variations of attenuation were found, it was decided to investigate the source of this variation. It was found that the fibers with higher attenuation were produced from preforms made in the same chemical vapor deposition (CVD) lathe. It is believed that the effect of this water peak can be greatly reduced with some work in optimizing the optical fiber.

3.1.3.6.1.1.2 Attenuation Versus Injection Numerical Aperture (INA)

The test plan requires that the attenuation of each fiber will be reported at all six wavelengths with an INA of 0.089 except that the 0.82 μm, four INA values will be reported. The selected values of INA are

Table 3.1.3.6.1.1-2. Attenuation Versus Wavelength (dB/km).

	Wavelength (μm)								Dispersion at 0.9 um
	0.82	0.85	1.05	1.09	1.1	1.2	1.3	1.4	(ns/km)
Design 1 - Cable 020979-MA-11 (1091 m long)									
Fiber #									
1	4.80	4.14	2.55	2.46	2.15	1.71	2.22	17.04	0.40
2	3.91	3.41	1.76	1.73	1.65	1.49	1.91	17.58	1.33
3	3.70	3.31	1.74	1.68	1.57	1.33	1.21	4.17	0.45
4	4.04	3.36	1.90	1.70	2.20	2.05	2.91	18.75	1.34
5	3.98	3.51	1.81	1.64	1.65	1.35	1.36	3.64	1.17
6	4.81	4.45	2.76	2.74	2.30	2.06	2.02	4.17	0.50
7	5.15	4.55	2.56	2.36	1.95	1.51	1.78	17.31	0.57
Design 2 - Cable 022679-MA-II (1099 m long)									
1	4.77	4.30	3.07	3.10	2.96	2.74	2.69	8.85	0.47
2	3.97	3.27	2.00	1.82	1.58	1.32	1.27	4.47	0.50
3	5.12	4.33	2.45	2.26	1.67	1.44	1.6	15.9	1.41
4	3.68	3.04	1.65	1.48	1.40	1.19	1.44	13.44	0.47
5	4.39	3.88	2.30	2.18	2.62	2.36	2.52	14.07	0.32
6	4.24	3.75	2.16	2.03	2.14	4.62	2.03	9.45	0.70
Design 3 - Cable 030279-MA-II (1100 m long									
1	5.04	4.54	3.04	2.62	2.78	2.51	2.41	11.45	0.30
2	3.92	3.51	1.88	1.71	1.59	1.40	1.58	12.71	0.30
3	4.33	3.83	2.02	2.07	1.71	1.50	1.62	10.69	0.11
4	4.22	3.91	2.24	2.04	2.11	1.87	1.90	10.44	0.26
5	4.26	3.86	2.29	2.13	1.89	1.71	1.89	13.44	0.33
6	4.80	4.41	2.74	2.59	2.72	2.55	2.68	10.33	0.66

- 0.089
- 0.124
- 0.176
- 0.243

Table 3.1.3.6.1.1.2-1 lists the results of attenuation measured at the four INA when the wavelength was 0.82 μm. Table 3.1.3.6.1.1.2-2 shows the results of attenuation measured at the same four INA when the wavelength was 1.2 μm. It can be seen that the attenuation at INA of 0.089 and 0.124 are very close; however, as the INA increases to 0.176 and 0.243, the attenuation also increases.

3.1.3.6.1.2 Pulse Dispersion

3.1.3.6.1.2.1 Specification

The specification for pulse dispersion was 2 ns/km maximum.

The 50% optical pulse dispersion of the fiber was measured using equipment operating at 9000 Å. Table 3.1.3.6.1.1-2 shows the dispersion of each fiber of cable designs 1, 2, and 3.

The 2 ns/km maximum dispersion goal was achieved and exceeded by a substantial margin.

Table 3.1.3.6.1.1.2-1. Attenuation Versus Injection Numerical Aperture (Wavelength 8200 Å).

Cable Design	Fiber No	Injection NA			
		0.089	0.124	0.176	0.243
1	1	4.80 dB/km	4.75 dB/km	5.52 dB/km	5.95 dB/km
	2	3.91	3.96	4.48	4.71
	3	3.70	4.00	3.88	3.96
	4	4.04	3.97	4.56	4.91
	5	3.98	3.77	3.91	3.78
	6	4.81	4.82	4.98	5.20
	7	5.15	5.39	5.90	6.20
2	1	4.77	4.94	4.94	5.23
	2	3.97	4.13	4.11	4.19
	3	5.12	5.25	5.26	5.45
	4	3.68	3.85	4.01	4.20
	5	4.39	4.36	4.48	4.21
	6	4.24	4.41	4.50	4.64
3	1	5.04	5.29	5.71	6.25
	2	3.92	4.04	4.24	4.53
	3	4.33	4.63	4.71	5.30
	4	4.22	4.52	4.66	5.10
	5	4.26	4.48	4.73	5.24
	6	4.80	4.95	5.28	5.51

Table 3.1.3.6.1.1.2-2. Attenuation Versus Injection Numerical Aperture (Wavelength 12000 Å).

Cable Design	Fiber No	Injection NA			
		0.089	0.124	0.176	0.243
1	1	1.71 dB/km	1.99 dB/km	2.57 dB/km	3.04 dB/km
	2	1.49	1.41	1.81	2.12
	3	1.33	1.24	1.55	1.70
	4	2.05	2.15	2.34	2.68
	5	1.35	1.38	1.49	1.63
	6	2.06	2.06	2.23	2.65
	7	1.51	1.40	1.76	2.15
2	1	2.74	2.73	3.02	3.37
	2	1.32	1.37	1.60	1.68
	3	1.44	1.43	1.65	1.89
	4	1.19	1.14	1.45	1.73
	5	2.36	2.51	2.76	2.92
	6	4.62	4.78	5.03	5.23
3	1	2.51	2.75	3.07	3.32
	2	1.40	1.51	1.71	2.01
	3	1.50	1.61	1.80	2.08
	4	1.87	2.09	2.41	2.84
	5	1.71	1.87	2.21	2.44
	6	2.55	2.72	2.94	3.11

3.1.3.6.1.3 Numerical Aperture (NA)

3.1.3.6.1.3.1 Specification

The specification for numerical aperture was 0.14 minimum.

Table 3.1.3.6.1.3.1-1 lists the NA of the fibers of cable designs 1, 2, and 3.

All cabled fibers of the three cable designs exceeded the minimum NA requirement.

3.1.3.6.2 Mechanical Tests

3.1.3.6.2.1 Impact Resistance

3.1.3.6.2.1.1 Specification

The specification was 200 impacts at 0.415 kg/m (objective) with no fiber breakage.

This test was performed in accordance with paragraph 3.7.2 of MIL-C-13777F at ambient temperatures of +21°C, +71°C, and -54°C. Table 3.1.3.6.2.1.1-1 shows the impact resistance of the cable designs 1, 2, and 3. Test measurements were made at 3.33, 3.73, 4.00, 4.66, 5.33, and 6 μm (2.47, 2.75, 2.95, 3.44, 3.93, 4.43 ft•lb). The corresponding test loads used on the impact tester shown in Figure 3.1.3.6.2.1.1-1 were 5 lb, 5.6, 6.0, 7.0, 8.0, and 9 lb.

Table 3.1.3.6.1.3.1-1. Numerical Aperture.

Fiber No	Cable Design 1	Cable Design 2	Cable Design 3
1	0.21	0.19	0.19
2	0.19	0.20	0.20
3	0.19	0.20	0.21
4	0.20	0.21	0.20
5	0.17	0.21	0.21
6	0.20	0.20	0.15
Center	0.20	-	-

Table 3.1.3.6.2.1.1-1. Impact Resistance.

Cable Design	Temperature (°C)	No of Cabled Fibers	Transmitting/ Broken	% Surviving Fibers
1	+21	42	42/0	100
	+71	42	42/0	100
	-54	42	41/1	97.6
2	+21	36	36/0	100
	+71	36	36/0	100
	-54	36	36/0	100
3	+21	36	36/0	100
	+71	36	36/0	100
	-54	36	36/0	100

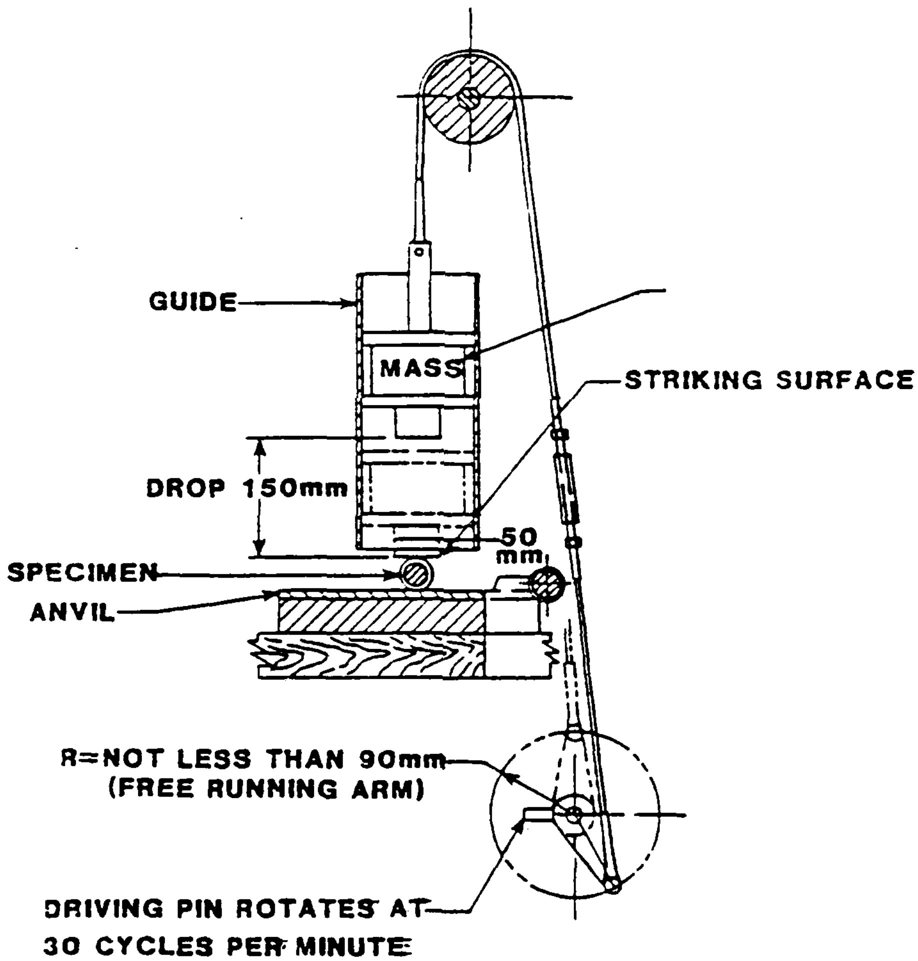


Figure 3.1.3.6.2.1.1-1. Impact Test Apparatus.

The 100% survivability goal was achieved in all three designs at +21°C and +71°C. Designs 2 and 3 also met this goal at -54°C. Cable design 1 had one broken fiber in one of the six samples; this brought the percentage of surviving fibers to 97.6% after 200 impacts at a load of 0.415 kg/m when tested at -54°C. This was considered one of the most difficult goals of this contract.

3.1.3.6.2.2 Bend Test

3.1.3.6.2.2.1 Specification

The specification was 2000 cycles without fiber breakage when tested for paragraph 3.7.2 of MIL-C-13777F.

The tests were performed at +21°C, +71°C and -54°C. Table 3.1.3.6.2.2.1-1 shows the performance of the cabled fibers during the bend test. The goal of 100% surviving fibers after 2000 cycles, at room temperature and extreme temperatures, was achieved with all three cable designs.

3.1.3.6.2.3 Twist Test

3.1.3.6.2.3.1 Specification

The specification was 2000 cycles without fiber breakage when tested per paragraph 3.7.2 of MIL-C-13777F. These tests were performed at +21°C, +71°C, and -54°C.

Table 3.1.3.6.2.3.1-1 shows the performance of cable designs 1, 2, and 3 when exposed to the twist test.

Table 3.1.3.6.2.2.1-1. Bend Test.

Cable Design	Temperature (°C)	No of Cabled Fibers	Transmitting/ Broken	% Surviving Fibers
1	+21	21	21/0	100
	+71	21	21/0	100
	-54	21	21/0	100
2	+21	18	18/0	100
	+71	18	18/0	100
	-54	18	18/0	100
3	+21	18	18/0	100
	+71	18	18/0	100
	-54	18	18/0	100

Table 3.1.3.6.2.3.1-1. Twist Test.

Cable Design	Temperature (°C)	No of Cabled Fibers	Transmitting/ Broken	% Surviving Fibers
1	+21	21	21/0	100
	+71	21	21/0	100
	-54	21	21/0	100
2	+21	18	17/1	94
	+71	18	18/0	100
	-54	18	18/0	100
3	+21	18	18/0	100
	+71	18	18/0	100
	-54	18	18/0	100

Cable designs 1 and 3 met the 100% survivability goal at all testing temperatures. There was one fiber break after 1480 twist cycles on cable design 2 when tested at room temperature. Cable design 2 met the goal of 100% survivability at +71°C and -54°C.

It must be noted that the testing equipment had just been received and was found to barely fit into the temperature chamber. The top sheave arrangement was not satisfactory and caused undue damage to the cable jacket. Due to schedule limitations, it was not possible to replace it. It was suspected that this arrangement was responsible for the fiber break.

Despite this broken fiber, the cable proved to have 94% of its tested fibers continuous after 2000 cycles. It was projected that by using a proper sheave, all cable designs at all temperatures will pass this test without fiber breakage.

3.1.3.6.2.4 Tensile Load

3.1.3.6.2.4.1 Specification

The specifications were for

• Gage length	6 m
• Load	181.44 kg for 1 min
• Postload attenuation	<5 dB/km
• Visual	No damage or degradation

Data on long term effects of the static load is obtained by applying the load for a period of 48 h, during which the transmission through the fibers is monitored.

It was assumed that because there was no visual degradation and the optical performance of the cable would improve, it would be most beneficial to test directly for long term degradation effects. Therefore, the 1 min under load test was not performed.

Two samples of cable design 3 were tested for tensile load effect on fiber attenuation. Noncontinuous attenuation monitoring was used. The cable gage length was 6 m.

Difficulties were found on the first sample of cable design 2; the cable elongation and test mandrel rotation with 6 m half loop exceeded the extension range of the tensile load equipment. To overcome this problem, a complete loop was used (approximately 12.5 m gage length) during this and the remaining tests.

The first sample of cable design 2 was tested using manual data acquisition. The remaining three tests were performed using an eight channel strip chart recorder. This enabled continuous monitoring of differential attenuation throughout the 48 h test period.

Tables 3.1.3.6.2.4.1-1 through 3.1.3.6.2.4.1-6 show the test results of cable designs 1, 2, and 3, respectively.

These results indicate that the long term effects of the tensile load on the optical performance of cable designs 1, 2, and 3 are very small. The visual inspection indicated that the strength members and the optical core had some position shifting; however, after the load was released, they slowly returned to the original positions.

Appendix A shows the test report from Aerospace Research Corporation.

3.1.3.6.2.5 Vibration

3.1.3.6.2.5.1 Specifications

The specifications were

- Vibration environment: Per Curve W, Figure 14.2-6 of MIL-STD-810C, see Figure 3.1.3.6.2.5.1-1
- Sweeps: Three parallel to sample axis, three orthogonal to sample axis
- Sweep time: 15 min
- Posttest cable properties: Attenuation <5 dB/km at specified wavelengths (see paragraph 3.1.1 of cable test plan, Appendix A)

Tables 3.1.3.6.2.5.1-1 through 3.1.3.6.2.5.1-3 list the results of the previbration and postvibration attenuation of each fiber of cable designs 1, 2, and 3.

Table 3.1.3.6.2.4.1-1. Tensile Load Test - Differential Attenuation (dB).

Cable Design 1, Sample No 1

Time	Load	Fiber No 1	2	3	4	5	6
0 min	0 kg	0 dB	0 dB	0 dB	0.dB	0.dB	0.dB
1	182	0.095	0.053	0.109	0.036	0.033	0.117
2	184	0.095	0.065	0.109	0.044	0.033	0.137
7	186	0.095	0.053	0.109	0.044	0.033	0.139
12	184	0.081	0.041	0.087	0.027	0.014	0.099
32	182	0.053	0.029	0.065	0.018	0.014	0.099
1 h	193	0.067	0.041	0.087	0.027	0.033	0.119
2	193	0.081	0.065	0.109	0.062	0.052	0.139
6	183	0.053	0.090	0.065	0.088	0.168	0.179
1[illegible]	180	0.067	0.126	0.087	0.124	0.188	0.179
12	182	0.067	0.090	0.065	0.079	0.110	0.179
24	193	0.039	0.065	0.043	0.053	0.033	0.159
36	191	0.067	0.114	0.065	0.062	-0.005	0.179
48	184	0.067	0.102	0.087	0.053	-0.043	0.179
49	0	-0.016	0.029	0	0.018	-0.099	0.039

Table 3.1.3.6.2.4.1-2. Tensile Load Test - Differential Attenuation (dB).

Cable Design 1, Sample No 2

		Fiber No					
Time	Load	1	2	3	4	5	6
0 min	0 kg	0 dB	0 dB	0 dB	0.dB	0.dB	0.dB
1	207	0	0	.0	0.02	0	-0.01
2	207	-0.04	-0.04	-0.04	-0.02	-0.04	-0.04
3	207	0.04	-0.04	-0.04	-0.02	-0.04	-0.04
1 h	207	0.08	-0.03	-0.03	-0.01	0.08	-0.03
3	207	0.17	-0.05	0.06	-0.03	0.17	0.06
5	207	0.17	-0.05	0.06	-0.03	0.17	0.06
7	207	0.17	-0.05	0.06	-0.03	0.17	0.06
12	207	0.06	-0.06	0.06	-0.15	-0.05	0.06
16	207	0.03	-0.08	0.03	-0.18	-0.08	-0.08
18	147	0.06	-0.05	0.06	-0.15	-0.15	-0.05
20	191	0.06	-0.15	0.06	-0.10	-0.15	-0.05
22	190	0.06	-0.05	0.06	-0.03	0	0
25	205	0.17	-0.05	0.06	-0.03	0.12	Break

Table 3.1.3.6.2.4.1-2. Tensile Load Test - Differential Attenuation (dB) (continued).

Cable Design 1, Sample No 2 (continued)

		Fiber No					
Time	Load	1	2	3	4	5	6
0 min	0 kg	0 dB	0 dB	0 dB	0.dB	0.dB	0.dB
30 h	205	0.20	-0.03	0.09	0	0.20	-
36	193	0.17	-0.05	0.06	-0.15	-0.05	-
40	193	0.19	-0.11	0.07	-0.13	-0.02	-
43	193	0.18	-0.05	0.18	-0.18	-0.40	-
45	193	0.08	-0.16	0.08	-0.11	-0.39	-
48	193	0.11	-0.14	0.11	-0.08	-0.25	-
51	0	0.16	-0.05	0.16	-0.16	0.16	-

Table 3.1.3.6.2.4.1-3. Tensile Load Test - Differential Attenuation (dB).

Cable Design 2, Sample No 1

		Fiber No					
Time	Load	1	2	3	4	5	6
0 min	0 kg	0 dB	0 dB	0 dB	0.dB	0.dB	0.dB
1	188	0.11	0.11	0	0	0	0
2	188	0.11	0.11	0	0	0	0
3	188	0.11	0.11	0	0	0	0
2 h	188	0.05	0	-0.1	0	0	-0.05
3	188	0.01	0.01	-0.25	0.01	0.01	-0.01
6	188	0.11	0	-0.21	0.11	0.11	0
10	188	0.11	0.11	-0.21	0.11	0.11	0
13	188	0.17	0.17	-0.21	0.17	0.22	0.05
15	188	0.06	0.06	-0.32	0	-0.05	-0.05
20	188	0.21	0.16	-0.22	0.21	0.33	0.10
22	188	0.21	0.21	-0.22	0.21	0.39	0.21
24	188	0.23	0	-0.32	0.23	0.35	0.23
26	188	0.17	-0.05	-0.27	0.21	0.28	0.28

Table 3.1.3.6.2.4.1-3. Tensile Load Test - Differential Attenuation (dB) (continued).

Cable Design 2, Sample No 1 (continued)

		Fiber No					
Time	Load	1	2	3	4	5	6
0 min	0 kg	0 dB	0 dB	0 dB	0.dB	0.dB	0.dB
29 h	188	0.11	-0.11	-0.31	0.11	0.11	0.34
42	188	0.24	-0.12	-0.23	0.24	0.12	0.18
51	184	0.37	-0.12	0.17	0.37	0.30	0.50
60	184	0.18	0	-0.29	0.18	0	0.31
69	193	0.12	0	-0.23	0.12	-0.06	0.12
89	193	0.25	0	-0.23	0.25	-0.06	0.25
93	0	0.19	-0.06	-0.30	0.32	0.12	0.25

Table 3.1.3.6.2.4.1-4. Tensile Load Test - Differential Attenuation (dB).

Cable Design 2, Sample No 2

		Fiber No					
Time	Load	1	2	3	4	5	6
0 min	0 kg	0 dB	0 dB	0 dB	0.dB	0.dB	0.dB
1	200	0.22	0.29	0.22	0.11	0.06	-0.11
2	200	0.22	0.24	0.23	0.12	0.07	-0.40
3	200	0.22	0.24	0.23	0.12	0.07	-0.30
5	200	0.29	0.24	0.23	0.12	0.07	-0.40
2 hr	198	0.23	0.18	0.12	0.23	0.18	-2.77*
4	198	0.23	0.30	0.12	0.35	0.17	-2.65
9	198	0.31	0.37	0.14	0.54	0.26	-2.46
11	160	0.22	0.34	0.11	0.56	0.16	**
13	182	0.22	0.28	0.11	0.56	0.11	**
20	182	0.12	0.23	0.01	0.58	0.01	**
24	182	0.16	0.28	0.05	0.56	0.06	-2.73
26	182	0.13	0.30	Break	0.59	0.13	-2.76

Table 3.1.3.6.2.4.1-4. Tensile Load Test - Differential Attenuation (dB) (continued).

Cable Design 2, Sample No 2 (continued)

		Fiber No					
Time	Load	1	2	3	4	5	6
0 min	0 kg	0 dB	0 dB	0 dB	0.dB	0.dB	0.dB
33 h	182	0.17	0.30	-	0.60	0.11	-2.77
37	182	0.12	0.19	-	0.61	-0.10	-2.88
42	182	0.22	0.29	-	0.71	-0.12	-2.79
44	182	0.17	0.29	-	0.71	-0.11	-2.89
46	182	0.16	0.21	-	0.64	-0.14	-2.88
49	182	0.23	0.30	-	0.60	-0.05	-2.89
51	186	0.29	0.30	-	0.60	0	-2.65
53	0	0.18	0.14	-	0.53	-0.03	-2.75

*Decrease in loss is believed to be connected with malfunction in strip chart recorder in this channel.
**Problems with strip chart recorder.

Table 3.1.3.6.2.4.1-5. Tensile Load Test - Differential Attenuation (dB).

Cable Design 3, Sample No 1

		Fiber No					
Time	Load	1	2	3	4	5	6
-20 min	0 kg	0 dB	0 dB	0 dB	0.dB	0.dB	0.dB
-15	0	0.04	0.05	0.02	0.08	-0.02	0.05
- 5	23	0.04	0.07	0.03	0.08	-0.02	0.07
0	182	0.05	0.11	0.06	0.17	0	0.11
5	182	0.05	0.10	0.04	0.17	-0.01	0.11
15	213	0.05	0.10	0.05	0.16	-0.02	0.11
43	186	0.05	0.12	0.05	0.18	-0.01	0.12
1 h	182	0.04	0.13	0.05	0.18	-0.02	0.14
2	182	0.02	0.15	0.03	0.20	-0.03	0.17
4	195	0.01	0.14	0.03	0.20	-0.04	0.16
8	191	0	0.16	0.05	0.25	-0.05	0.21
13	186	0.01	0.08	0.03	0.18	-0.04	0.17
19	209	0.03	0.06	0.06	0.13	-0.01	0.14
31	184	0.01	0.12	0.06	0.28	-0.03	0.21
46	182	0.03	0.05	0.06	0.13	0	0.13
46	0	0.02	0.05	0.05	0.11	-0.02	0.12

Table 3.1.3.6.2.4.1-6. Tensile Load Test - Differential Attenuation (dB).

Cable Design 3, Sample No 2

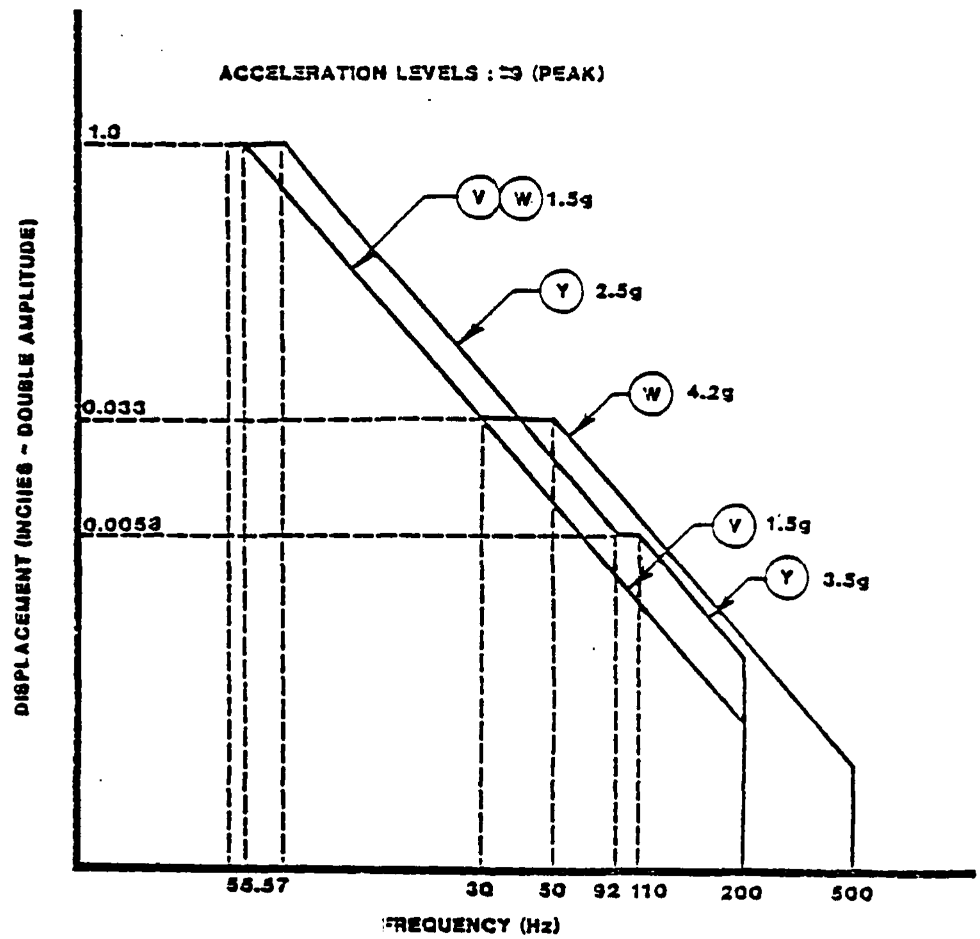
		Fiber No					
Time	Load	1	2	3	4	5	6
-20 min	0 kg	0 dB	0 dB	0 dB	0.dB	0.dB	0.dB
-10	23	-0.02	-0.02	0	0.041	-0.01	0.02
- 5	91	-0.01	-0.02	0	0.04	0	0.02
0	182	-0.01	0	0.02	0.07	0.01	0.04
1	182	-0.02	0	0.01	0.05	0.01	0.05
5	182	-0.01	0.01	0.02	0.07	0.01	0.05
10	182	-0.02	0.01	0.01	0.07	0.01	0.05
20	182	-0.02	0.01	0.01	0.07	0.01	0.06
30 h	273	-0.03	0.01	0.02	0.07	0.01	0.08
1	236	0	0.02	0.02	0.08	0.02	0.19
2	186	-0.03	-0.01	0	0.07	-0.01	0.25
4	259	-0.02	0.02	0.03	0.10	0.01	0.33
8	218	-0.04	-0.04	0.02	0.05	-0.04	0.45
16	204	-0.04	-0.05	0.02	0.05	-0.04	0.54

Table 3.1.3.6.2.4.1-6. Tensile Load Test - Differential Attenuation (dB) (continued).

Cable Design 3, Sample No 2 (continued)

		Fiber No					
Time	Load	1	2	3	4	5	6
-20 min	0 kg	0 dB	0 dB	0 dB	0.dB	0.dB	0.dB
20 h	204	-0.05	-0.05	0.02	0.08	-0.04	0.55
24	200	0.13	-0.05	0.03	0.08	-0.05	0.58
48	193	0.20	-0.07	0.05	0.14	-0.04	0.60
50	186	0.13	-0.05	0.05	0.61	0.04	0.60
50	0	0.13	-0.05	0.05	0.20	0.06	0.62
52	0	0.13	-0.09	0.05	0.13	0.01	0.63

MIL-STD-810C



NOTE: ALL CURVES SHALL BE EXTENDED TO 2 Hz WHEN TEST ITEM RESONANCES BELOW 5 Hz ARE EXPECTED.

Figure 3.1.3.6.2.5.1-1. Curve W, Figure 14.2.6, of MIL-STD-810C.

Table 3.1.3.6.2.5.1-1. Previbration and Postvibration Attenuation - Cable Design 1.

			Attenuation (dB/km)						
		Wavelength	0.82 μm				0.85	1.05	1.09
Fiber No	Measured	INA	0.089	0.124	0.176	0.243	0.089	0.089	0.089
1	Before Vib.		7.43	7.51	8.45	9.25	6.41	4.99	4.69
	After "		8.01	8.40	9.01	9.66	7.39	5.30	4.92
2	Before Vib.		3.88	3.95	4.33	4.81	4.17	1.98	1.67
	After "		4.24	4.41	4.64	5.59	3.67	2.15	1.04
3	Before Vib.		4.08	4.11	4.30	4.49	3.20	2.75	2.16
	After "		4.13	4.23	4.33	4.17	3.68	2.14	1.42
4	Before Vib.		4.79	4.88	4.90	5.07	5.99	3.24	2.88
	After "		5.53	5.72	6.29	6.47	5.04	2.91	2.69
5	Before Vib.		5.06	5.15	5.46	5.75	4.77	2.84	2.89
	After "		5.74	6.00	6.12	6.38	5.10	3.72	3.21
6	Before Vib.		5.72	5.80	6.25	6.37	4.52	3.96	3.67
	After "		5.55	5.71	5.86	6.26	4.95	3.38	2.93
7	Before Vib.		5.42	5.53	6.10	6.64	4.41	2.83	2.49
	After "		4.87	5.22	5.95	6.62	4.26	2.71	2.53
Average Δ Attenuation (dB/km)			0.24	0.39	0.34	0.40	0.09	-0.04	-0.24

Total Average Δ Attenuation = 0.17 dB/km

Table 3.1.3.6.2.5.1-2. Previbration and Postvibration Attenuation - Cable Design 2.

			Attenuation (dB/km)						
		Wavelength	0.82 µm				0.85	1.05	1.09
Fiber No	Measured	INA	0.089	0.124	0.176	0.243	0.089	0.089	0.089
1	Before Vib.		6.68	6.98	7.56	7.94	6.33	5.10	4.85
	After "		7.05	7.41	8.26	8.79	6.75	5.45	5.06
2	Before Vib.		4.66	4.90	5.18	5.30	4.34	2.88	2.78
	After "		5.21	5.93	5.85	6.23	4.80	3.21	2.84
3	Before Vib.		5.44	5.56	5.77	6.24	4.64	1.95	2.20
	After "		5.54	5.66	5.92	6.38	4.91	2.87	2.42
4	Before Vib.		3.98	3.94	4.06	4.46	3.41	2.05	1.85
	After "		3.89	4.20	4.52	5.13	3.42	1.91	1.78
5	Before Vib.		4.57	4.54	5.05	5.44	4.02	2.52	2.30
	After "		5.09	5.33	5.79	6.14	4.60	2.87	2.76
6	Before Vib.		5.72	5.87	5.97	6.51	5.13	3.58	3.52
	After "		6.18	6.48	6.98	7.41	5.60	4.28	3.77
7	Before Vib.		-	-	-	-	-	-	-
	After "		-	-	-	-	-	-	-
Average Δ Attenuation (dB/km)			0.32	0.54	0.62	0.65	0.37	0.42	0.19

Average = 0.44 dB/km
Δ Attenuation

Table 3.1.3.6.2.5.1-3. Previbration and Postvibration Attenuation - Cable Design 3.

			Attenuation (dB/km)						
		Wavelength	0.82 μm				0.85	1.05	1.09
Fiber No	Measured	INA	0.089	0.124	0.176	0.243	0.089	0.089	0.089
1	Before Vib.		4.98	4.95	5.61	6.33	4.30	2.97	2.66
	After "		5.15	5.34	6.02	6.66	4.65	2.98	3.01
2	Before Vib.		4.41	4.85	5.16	5.76	2.29	2.62	2.36
	After "		5.16	5.32	6.12	6.36	4.52	2.72	2.40
3	Before Vib.		4.66	5.01	5.54	6.51	4.44	2.68	2.46
	After "		5.03	5.34	5.96	6.70	4.51	3.00	2.90
4	Before Vib.		5.22	5.32	6.02	6.63	4.73	2.90	3.02
	After "		5.85	6.38	6.78	7.32	5.48	3.81	3.76
5	Before Vib.		5.18	5.21	5.32	5.41	4.20	2.39	2.55
	After "		5.03	5.44	5.90	6.35	4.54	2.92	2.92
6	Before Vib.		5.51	5.64	6.01	6.50	4.74	3.32	3.16
	After "		5.92	6.18	6.66	6.98	5.50	3.71	3.25
7	Before Vib.								
	After "								
Average Δ Attenuation (dB/km)			0.36	0.50	0.63	0.54	0.75	0.38	0.33

Average = 0.50 dB/km
Δ Attenuation

It must be noted that the cables exposed to the vibration test had been previously exposed to the temperature shock test and temperature humidity test. Some fibers had a pretest attenuation in excess of 5 dB.km.

It must also be noted that the average attenuation increase per fiber in cable design 1 was only 0.17 dB/km, in cable design 2 was 0.44 dB/km, and in cable design 3 was 0.50 dB/km.

3.1.3.6.3 Environmental Tests

3.1.3.6.3.1 Temperature Shock

3.1.3.6.3.1.1 Specification

The specifications were

- Test conditions: Per Method 503.1 of MIL-STD-810C. This requires testing at -57°C and +71°C.
- Posttest performance: Attenuation ≤5 dB/km at specified wavelengths

Tables 3.1.3.6.3.1.1-1 through 3.1.3.6.3.1.1-3 show the results of the thermal shock test.

Most fibers showed an attenuation in excess of the 5 dB/km goal before and after the test. These values are due to the shorter cable length which allows some interference of the higher order modes and the fact that the cables were already exposed to the humidity test.

Table 3.1.3.6.3.1.1-1. Results of Thermal Shock Test - Cable Design 1.

		Attenuation (dB/km)						
	Wavelength	0.82 μm				0.85	1.05	1.09
Fiber No	Measured / INA	0.089	0.124	0.176	0.243	0.089	0.089	0.089
1	Before Temp Shock	7.18	7.34	7.72	8.06	-	-	-
	After " "	7.43	7.51	8.45	9.25	6.41	4.99	4.69
2	Before Temp Shock	4.08	4.25	4.47	4.91	-	-	-
	After " "	3.67	3.84	4.07	4.52	3.13	1.25	1.47
3	Before Temp Shock	4.26	4.28	4.49	4.45	-	-	-
	After " "	4.19	4.32	4.23	4.58	3.70	1.88	1.98
4	Before Temp Shock	5.08	5.47	5.75	6.05	-	-	-
	After " "	5.19	5.31	5.62	6.21	4.52	2.79	2.76
5	Before Temp Shock	5.14	5.18	5.36	5.78	-	-	-
	After " "	5.10	5.13	5.37	5.82	4.66	3.29	2.83
6	Before Temp Shock	5.52	5.69	5.86	6.14	-	-	-
	After " "	5.40	5.65	5.87	6.10	4.76	3.13	3.05
7	Before Temp Shock	5.84	5.97	6.28	6.80	-	-	-
	After " "	5.69	5.74	6.03	6.41	5.07	2.98	2.88
Average Δ Attenuation (dB/km)		-.06	-0.10	-0.04	+0.10	-	-	-

Table 3.1.3.6.3.1.1-2. Results of Thermal Shock Test - Cable Design 2.

			Attenuation (dB/km)						
		Wavelength	0.82 µm				0.85	1.05	1.09
Fiber No	Measured	INA	0.089	0.124	0.176	0.243	0.089	0.089	0.089
1	Before Temp Shock		6.00	6.11	6.35	6.63	-	-	-
	After " "		6.68	6.98	7.56	7.94	6.33	5.10	4.85
2	Before Temp Shock		5.48	5.68	5.75	6.28	-	-	-
	After " "		4.66	4.90	5.18	5.30	4.34	2.88	2.78
3	Before Temp Shock		5.62	5.80	6.35	6.44	-	-	-
	After " "		5.44	5.56	5.77	6.24	4.64	1.95	2.20
4	Before Temp Shock		3.84	3.94	4.30	4.60	-	-	-
	After " "		3.98	3.94	4.06	4.46	3.41	2.05	1.85
5	Before Temp Shock		5.24	5.53	5.71	6.22	-	-	-
	After " "		4.57	4.54	5.05	5.44	4.02	2.52	2.30
6	Before Temp Shock		5.64	5.96	6.16	6.59	-	-	-
	After " "		5.72	5.87	5.97	6.51	5.13	2.58	3.52
7	Before Temp Shock		-	-	-	-	-	-	-
	After " "		-	-	-	-	-	-	-
Average Δ Attenuation (dB/km)			-0.13	-0.21	-0.17	-0.15	-	-	-

Table 3.1.3.6.3.1.1-3. Results of Thermal Shock Test - Cable Design 3.

Fiber No	Measured	Wavelength	Attenuation (dB/km) 0.82 μm				0.85	1.05	1.09
		INA	0.089	0.124	0.176	0.243	0.089	0.089	0.089
1	Before Temp Shock		5.63	5.65	6.07	5.97	-	-	-
	After " "		4.98	4.95	5.61	6.33	4.30	2.97	2.66
2	Before Temp Shock		4.51	4.71	4.84	5.13	-	-	-
	After " "		4.41	4.85	5.16	5.76	2.29	2.62	2.36
3	Before Temp Shock		5.51	5.90	6.43	6.60	-	-	-
	After " "		4.66	5.01	5.54	6.51	4.44	2.68	2.46
4	Before Temp Shock		5.55	5.58	6.08	6.67	-	-	-
	After " "		5.22	5.32	6.02	6.63	4.73	2.90	3.02
5	Before Temp Shock		4.96	5.31	5.69	6.08	-	-	-
	After " "		5.18	5.21	5.32	5.41	4.20	2.39	2.55
6	Before Temp Shock		5.58	5.76	5.87	6.40	-	-	-
	After " "		5.51	5.61	6.14	6.52	4.85	2.98	2.96
7	Before Temp Shock		-	-	-	-	-	-	-
	After " "		-	-	-	-	-	-	-
Average Δ Attenuation (dB/km)			-0.30	-0.33	-0.20	+0.05	-	-	-

The attenuation measured after the temperature shock shows very little change, and it decreases in all but one case. This statement is based on measurements at 0.82 μm wavelength. Unfortunately, no pretest measurements were performed at 0.85, 1.05, and 1.09 μm.

3.1.3.6.3.2 Temperature/Humidity Test

3.1.3.6.3.2.1 Specifications

The specifications were

- Test conditions: Per Method 507.1, Procedure II, MIL-STD-810C, deleting measurements during testing, see Figure 3.1.3.6.3.2.1-1
- Posttest performance: Attenuation <5.0 dB/km at specified wavelengths

The differential attenuation was measured during the test. This deviation of test procedure provided substantial information in addition to the posttest performance.

From Tables 3.1.3.6.3.2.1-1 through 3.1.3.6.3.2.1-3, it can be seen that cable design 2 has increases in attenuation which are substanially higher than those of cable designs 1 and 3. Cable design 3 performed best if the performance of fiber no 4 of cable design 1 is disregarded. The performance of cable designs 1 and 3 is equivalent.

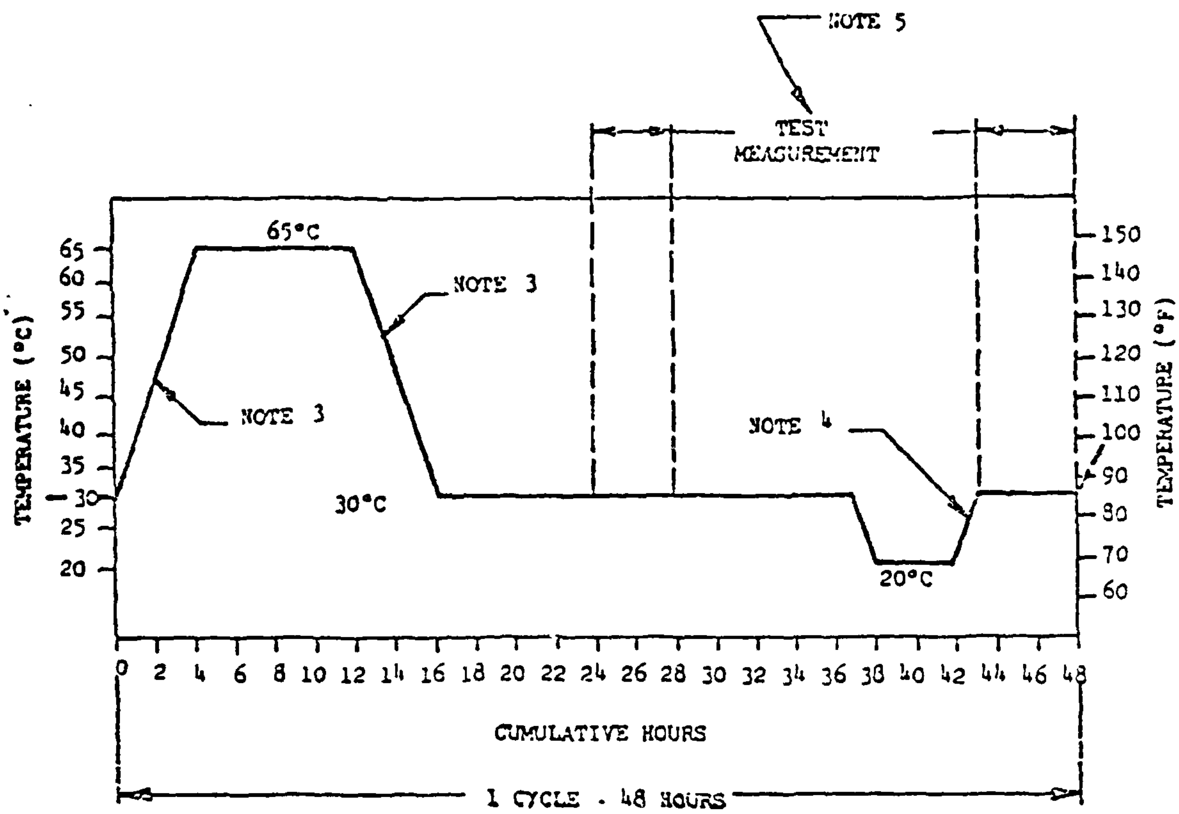


Figure 3.1.3.6.3.2.1-1. Method 507.1, Procedure II, MIL-STD-810C.

Table 3.1.3.6.3.2.1-1. Temperature/Humidity Test - Cable Design 1

Temp (°C)	RH	Fiber 1	2	3	4	5	6
65	98%	0.64	0.93	0.37	1.39	0.72	0.21
30	96	1.02	1.54	1.42	3.38	0.79	1.67
19	95	1.32	1.81	1.86	3.81	0.90	2.24
30	84	0.96	1.49	1.23	2.98	0.82	1.42
65	84	0.84	1.10	0.72	2.25	0.73	0.72
30	95	1.46	1.66	1.78	4.05	0.75	2.34
19	88	1.78	1.84	2.10	4.34	0.81	2.65
29	95	1.48	1.66	1.75	4.05	0.75	2.21
65	96	0.76	1.04	0.62	2.25	0.68	0.65
30	95	1.51	1.66	1.86	4.05	0.78	2.45
20	92	1.84	1.84	2.18	4.29	0.84	2.77
30	87	1.51	1.66	1.83	4.00	0.81	2.37
65	96	0.91	1.22	0.91	2.57	0.79	1.05
30	95	1.83	1.78	1.98	4.52	0.79	2.74
20	92	1.92	1.89	2.22	4.29	0.87	2.85
30	95	1.64	1.74	2.02	4.08	0.81	2.62
23	88	1.87	1.84	2.27	4.25	0.81	2.85
22	86	1.80	1.84	2.27	4.17	0.81	2.80
5 days later							
24	86	0.99	1.39	1.16	2.50	0.72	1.16

AD-A132 007 ULTRA LOW LOSS OPTICAL FIBER CABLE ASSEMBLIES VOLUME 1 (U) ITT ELECTRO-OPTICAL PRODUCTS DIV ROANOKE VA C HAND 07 JUN 83 ITT-80-22-07-VOL-1 CECOM/DRSEL-TR-78-2922F-1

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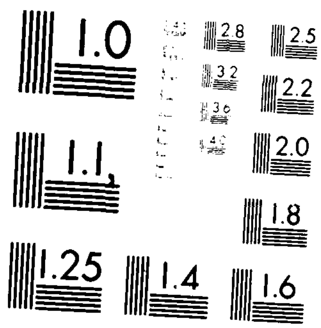

MICROCOPY RESOLUTION TEST CHART

Table 3.1.3.6.3.2.1-2. Temperature/Humidity Test - Cable Design 2

Temp (°C)	RH	Fiber 1	2	3	4	5	6
65	98%	1.52	0.15	1.03	1.09	1.40	0.91
30	96	2.17	0.62	1.87	1.80	2.12	2.18
19	95	1.65	1.08	2.26	2.26	2.61	3.50
30	84	1.98	0.62	1.78	1.55	1.86	1.71
65	84	1.86	0.35	1.52	1.70	1.99	1.71
30	95	2.64	0.91	2.12	2.35	2.73	3.72
19	88	2.89	1.14	2.35	2.48	2.80	4.23
29	95	2.65	0.97	2.17	2.30	2.63	3.33
65	96	1.90	0.29	1.47	1.71	2.01	1.64
30	95	2.55	0.86	2.08	2.32	2.65	3.57
20	92	2.85	1.11	2.35	2.51	2.80	4.40
30	87	2.48	0.88	2.08	2.23	2.54	3.16
65	96	1.95	0.34	1.59	1.86	2.12	3.01
30	95	2.79	0.91	2.21	2.49	2.79	4.28
20	92	2.03	1.14	2.35	2.54	2.80	4.53
30	95	2.60	1.05	2.21	2.37	2.80	3.79
23	88	2.86	1.22	2.39	2.52	2.80	4.23
22	86	2.80	1.22	2.39	2.51	2.80	4.23
5 days later							
24	86	2.11	0.81	2.12	1.80	2.04	2.01

Table 3.1.3.6.3.2.1-3. Temperature/Humidity Test - Cable Design 3

Temp (°C)	RH	Fiber 1	2	3	4	5	6
65	98%	0.30	0.00	0.38	0.66	0.39	0.48
30	96	0.59	0.80	0.66	1.10	-	0.98
19	95	0.87	1.34	0.89	1.47	1.43	1.38
30	84	0.53	0.68	0.66	0.98	1.01	0.86
65	84	0.48	0.36	0.48	0.96	0.66	0.78
30	95	0.98	1.47	0.84	1.64	1.43	1.55
19	88	1.20	1.80	0.99	1.89	1.68	1.82
29	95	0.93	1.34	0.84	1.58	1.38	1.49
65	96	0.56	0.47	0.57	1.08	0.75	0.90
30	95	1.04	1.55	0.84	1.73	1.46	1.65
20	92	1.32	2.00	1.02	2.03	1.77	1.98
30	87	0.96	1.41	0.84	1.61	1.38	1.52
65	96	0.63	0.68	0.63	1.22	0.87	1.05
30	95	1.28	1.97	0.99	2.03	1.14	2.03
20	92	1.41	2.12	1.05	2.12	1.86	2.13
30	95	1.16	1.77	0.92	1.85	1.62	1.82
23	88	1.34	2.06	1.05	2.03	1.82	2.04
22	86	1.34	2.06	1.05	2.03	1.82	2.04
5 days later							
24	86	0.90	1.34	0.86	1.46	1.38	1.35

The effects of the temperature/humidity test are not reversible in the short term; however, they completely recover their transmission characteristics in the long term, as is shown after the temperature shock and vibration tests.

3.1.3.6.4 Conclusions

The optical specifications for this contract were achieved and, in several cases, exceeded by a substantial margin. The measurements at long wavelength provide useful data for future long repeater spacing systems.

The mechanical goals were also achieved, including the impact resistance test, which was considered the most difficult goal of this contract. Further improvement in this area was sacrificed in order to make the fibers more compatible with the connectors that are being designed.

The cumulative effect of the temperature/humidity, temperature shock, and vibration tests tend to slowly increase the attenuation (0.86 dB/km average at 0.82 μm).

Based on the available data, the three cable designs meet the goal of this contract.

3.2 Cable Assembly Results

The cable assembly evaluation followed the component development of the cable and connector. The plan consisted of evaluating, performing, and testing each of the steps necessary to assemble the cable to the connectors and finally testing the cable assemblies. CLIN items 0003 (six pigtails with plugs), 0004 (six pigtails with receptacles), 0005 (three 1-km assemblies), and 0006 (two pigtails with bulkhead receptacles) were fabricated and used in these tests. The detailed plan for this design development was delivered as CLIN 0007/A003b (Design Plan, Cable, Connector, and Cable Assembly Design).

The assembly development addressed:

- Fiber bend losses in connector backshell
- Channel losses
- Terminal assembly procedure and repairability
- Strain relief and connector clamp
- Channel continuity for hermaphrodicity
- Mating characteristics
- Interface cleaning
- Environmental sealing
- Connector/cable assembly (simplicity)

3.2.1 Connector Development

The connector design developed for this contract is an hermaphroditic connector for field use. It includes a bulkhead receptable for panel mounting feed-through interface. The connector is designed for a six fiber cable with the insertion loss goals of 1.0 dB and 1.5 dB for the plug-to-plug and the plug-to-receptacle interfaces, respectively.

Two types of connectors were used and described in the course of the ultra low loss cable assembly development. ITT Cannon did the initial connector development. An industry search showed that Hughes Aircraft Co had developed a connector with the desired properties. Hughes completed the development with a second design. The tolerance buildups of standard electrical connectors used by ITT Cannon was too great for repeatable low loss optical connectors. An evaluation or corrective design options indicated a specialized connector body was necessary.

3.2.2 Connector Selection

The connector development plan was to conduct an industry survey and execute a "make or buy" decision based on the state-of-the-art determined therefrom. The plan was to develop or purchase connectors for evaluation and for the cable assembly and finally to test the connectors. The final step was accomplished in conjunction with the cable assembly tests. The hermaphroditic connector plug and bulkhead receptacle design plan was submitted as part of CLIN 0007/A003b. A copy is attached as part of Appendix A.

The connector development, at the outset, was contingent upon the alternative cable designs. During the first quarter of 1979, samples of each of three cable designs were prepared and supplied to ITT Cannon. ITT Cannon provided detailed drawings of the components required to install JF in the CECOM six-channel connector. Design review and prototype fabrication followed. The ATS ferrule and six-channel connector were originally designed to terminate Corning fiber, which is of a different design than ITT EOPD fiber. Consequently, the ATF design needed to undergo further efforts to make it compatible with the ITT EOPD fiber design. A program review was held during the first quarter of 1979 and a new connector schedule was developed. These efforts are reviewed in the following paragraphs.

Four mated pair connectors including all hardware components were made ready for a critical design review (CDR). ITT EOPD fiber, cable construction, and design were different from the Corning fiber and cable, which necessitated some redesign of the connector strength member clamp strain relief mechanisms and sealing components. A total of 24 ATS ferrule assemblies and 24 JF subassemblies were evaluated on September 13, 1979, the JF connector was selected over the ATF ferrule assembly approach. Major considerations in the decision were time needed to complete the work and cost. The JF approach was considered more likely to succeed.

At this point, the ITT Cannon subcontractor was placed on hold, and there ensued a number of delays and adjustments in the contract. Finally, in May 1980, contract cost adherence dictated a reduction in the quantity of hardware deliverables.

Because of a series of delays and lack of performance on the part of ITT Cannon, in early 1981 ITT EOPD with the support of CECOM terminated the subcontract which had been placed with ITT Cannon. CECOM suggested that Hughes be contacted and considered as a replacement for ITT Cannon for the connector development. ITT EOPD initiated the action after further investigation and with CECOM's agreement placed a purchase order to Hughes Aircraft Co., Connecting Devices Division, in Irvine, California. The purchase order specified all hardware and termination of the connectors to the final cable design produced by ITT EOPD. An additional purchase order was placed for the connector qualification testing.

3.2.3 ITT Cannon Development

Previously ITT Cannon Electric was involved in a fiber optic connector program encompassing commercial, industrial, and military fiber optic markets. Coupled with ITT EOPD which manufacturers fiber and cable and ITT's Avionics and Electronics Systems

Division, Cannon fiber optic connectors were selected to implement and complement fiber optic work for this contract because efforts had been centered on both bundle and single fiber interconnection systems. Achievements have included 3 dB fiber-to-fiber bundle connectors and the implementation of several single fiber connector systems. Efforts at ITT Cannon included fiber optic bus systems, source and detector to fiber bundle connectors, as well as fiber to fiber connectors.

A variety of multichannel and single-channel connectors had been developed under USA ECOM contract DAAB07-76-C-1357. This work was the basis for ITT Cannon's present three-sphere ferrule design concept which is capable of 1 dB interconnection loss. The resulting connector hardware and ferrule alignment concept was evaluated for use in this contract.

In addition to the three-sphere ferrule approach currently under development by ITT Cannon, a precision jewel ferrule connector developed by ITT Leeds (U.K.) has been used extensively by ITT EOPD in systems applications. Both single and multiway designs have been used for commercial and military system installations.

Preliminary data from a field installation of single way connectors using ITT EOPD's most current installation technique showed an average loss of less than 1.3 dB on 50 μm core graded-index fibers. Although the installation and evaluation was accomplished under less than ideal field conditions, the yield of usable ferrules was greater than 90% and a number of connectors had losses below 1 dB. By tightening component and fiber tolerances, it was expected but 1 dB connector loss could be repeatably achieved with this connector approach.

Table 3.2.3-1 was derived from testing done jointly by ITT, Hughes, and GTE personel at the Roanoke ITT EOPD plant in January 1982. Cable samples were terminated using both the old Hughes method and the ITT method. The Hughes method produced failures which confirmed their earlier experience. The new technique was performed by each company represented. The only failure occurred on a first attempt by ITT personel to demonstrate. The remainder were satisfactory.

3.2.3.1 Terminal Assembly

The terminal assembly procedure is critical to ultimate connector performance. The fiber must be positioned firmly, with no damage, and with a rugged resistance to temperature extremes and mechanical shock.

In this development two types of contact design were evaluated: (a) the ATS design and (b) the JF design. These two approaches offer superior alignment of the fiber.

Table 3.2.3-1. Test Results.

Test Cycle IV. Temperature cycle

New assembly technique summary (ITT):

1. Strip cable inner and outer jacket.
2. Clean ink off fiber jacket with acetone and paper towel.
3. Strip Hytrel® jacket to expose ≈3/4 in to 1 in of bare fiber.
4. Clean RTV buffer off fiber with propanol-2 and paper towel.
5. Slide correct size contact over fibers and install in heat fixture.
6. Pull (retract) fiber out of contact ≈1/16 in to 1/8 in and tape in place.

   NOTE: Only ≈1/16 in of bare fiber will extend out of contact.
7. Preheat fixture to +50°C to +60°C (for ≈10 min).
8. Mix Epo-tek 330D epoxy 10 to 1 pbw and de-air.
9. Using toothpick, apply epoxy to back of contact and permit it to wick in.
10. Apply epoxy at weep hole and permit it to wick in.
11. Attach syringe (plunger depressed) and tubing to contact end. Pull plunger out <u>slowly</u> while adding additional epoxy at weep hole and back of contact as required until evidence of epoxy around fiber end is seen. Remove tubing and inspect for epoxy bead.
12. Add drop of epoxy to contact end to support fiber.
13. Cure epoxy for at least 30 min at +95°C to +100°C.

3.2.3.2 ATS Evaluation

The ATS approach was observed to cause localized stresses in the fiber at the contact points. It was noted the fiber tended to break more readily during ferrule termination to close the spheres radially inward upon the fiber. A specifically designed tool, an assembly torque wrench, contains a slip clutch set to preclude fiber crushing. Since a random nature to the fiber breakage was noticed, a study of fiber strength under crush loads was conducted.

The fiber crush tests were accomplished in a fixture containing three spheres simulating an ATS ferrule. Two spheres are fixed and tangent to each other in the fixture. A third sphere is radially movable and gage mounted. The force to crush is measured while observing under a microscope. The results indicated a range of crush forces from 0.4 to 8.0 lb with an average of 2.8 lb.

Further tests were conducted to attempt a correlation with fiber diameter. The fiber was tested at increments of 0.200 in for a 6-in length. When plotted, no correlation to diameter was found (note diameter from 124 μm to 133 μm on several samples) and the crush force data appear to have a periodic function which correlate to the period of helical wrap within the cable. The relationship may be due to the stresses induced in the fiber during cabling, a compression on the surface of the fiber toward the cable center, and a tension opposite this.

When Corning step-index fiber was tested similarly, a narrower range of data resulted with an average of approximately 5.0 lb. This presented an unacceptable variable in the production cycle, precluding the use of the ATS design.

3.2.3.3 Jewel Ferrule Evaluation

During coupling loss and durability testing, the jewel ferrules exhibited wear from sliding contact with the male guide sleeves and a range of interface attenuation between 1 dB and 10 dB. Further development would have been necessary to utilize the Cannon JF.

3.2.3.4 Fiber Bend Losses at Connector Backshell

When a pair of connectors is mated, the abutting ferrules must move aft to absorb component dimensional tolerances. Since the connector strength member is secured at the back of the connector, the fiber is forced to flex within a chamber provided between the ferrule and the Kevlar® clamp. This flexure was suspected of contributing to the attenuation and masking the actual connector loss in evaluation tests. This was verified by pulling on the cable which stretched the Kevlar®, thus reducing curvature of the fiber. The connector used to perform this test was an ITT Cannon with jewel ferrule. The attenuation was improved, verifying the effect. The data for the measurement is shown in Table 3.2.3.4-1.

Table 3.2.3.4-1. Data Measurement (CLIN B001 Bimonthly June-July 1979).

	Average of 10 Matings	
Channel	Tension Free	Under Pull
1	3.17	1.8
2	3.59	2.1
3	-	-
4	10.08	7.6
5	2.51	1.6
6	1.41	0.8

Note: Channel 3 - fiber broke under assembly and gave erratic readings.

The radius of curvature was clearly a consideration which must be controlled. To design a backshell to control or eliminate this effect, a study was made to measure the loss as a function of curvature. To do this, samples of the fiber were subjected to flexure under controlled curvature and the change in throughput power was measured. The conclusion was that limiting axial displacement to <0.25 in was sufficient to prevent unacceptable losses in backshell chambers that were >1.25 in.

3.2.3.5 Channel Losses

Due to the differences between ITT and Corning cable construction and size, the connector strength member clamp strain relief mechanisms and sealing components were modified. Sufficient ATS and JF connector components were manufactured to yield two mated connector assemblies. The jeweled ferrules and ATS ferrules were designed to be interchangeable within the connector body. This would allow alignment concept evaluation without changing the costly connector components.

A total of 24 ATS ferrules was received from the vendor for evaluation. A dimensional inspection of all components was performed, and it was found that the gap control spring was not properly closed and ground. This would affect the uniform pressure needed to seal the ferrules from the environment. Several ferrules were terminated (using cable design 3) in the connector housing and the coupling was measured. A random instability problem was observed in the ferrule positioning. The ferrules were slightly modified and retested. The instability problem was eliminated. A few of the random matings exhibited coupling losses over 1 dB, and it is believed that these matings are due to factors such as dust, keying, and core diameter variations. Table 3.2.3.5-1 shows the coupling losses of 263 matings.

Coupling losses lower than 1 dB were found in 225 matings. Thirty-five matings had coupling losses lower than 2 dB, and only three exceeded 2 dB.

3.2.3.6 ITT Cannon Cable Strain Relief

The connector cable strain relief and strength member clamp isolates the optical fibers and connector termini from direct tensile, torsional, and bending forces applied between the connector and cable. The cable clamp incorporates a taper fit clamp (Figure 3.2.3.6-1a) and ring (Figure 3.2.3.6-1b) which will capture the Kevlar® strength member of the cable. The inner clamp provides a radius about which the Kevlar® is dressed. The outer ring fits over the inner clamp to capture the Kevlar®. This clamp has been tested with ultra low loss cable design 3 and proved to hold more than the 181.44 kg (400 lb) required. The connector clamp nut prevents loosening from vibration, temperature extremes, or shock.

Table 3.2.3.5-1. Adjustable Three-Sphere Coupling Losses.

Coupling Loss (dB)	Frequency
0.10	8
0.20	16
0.30	36
0.41	28
0.51	28
0.61	32
0.71	31
0.81	26
0.92	20
1.02	2
1.12	10
1.22	4
1.33	10
1.43	5
1.63	1
1.84	1
1.94	2
2.35	1
2.55	1
3.58	1
Total Evaluated	263

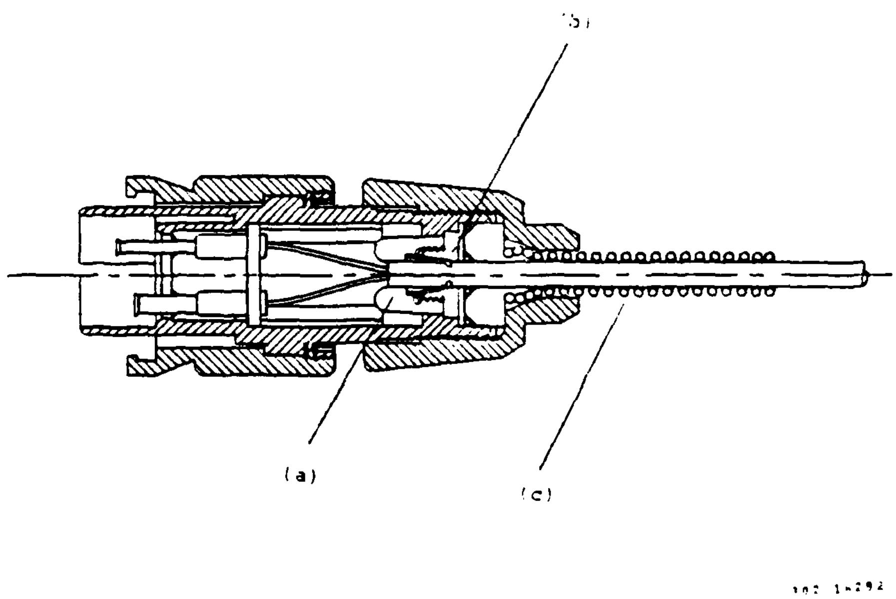

Figure 3.2.3.6-1. Cannon Strength Member Tie-Off.

The cable grip (Figure 3.2.3.6-1c) will provide resistance to cable twist and forces which tend to push the cable toward the interface of the connector. It clamps onto the jacket of the cable as the slotted fingers are forced inward by the tapered inside diameter of the nut. The closed diameter of the fingers is controlled to prevent too much or too little clamping force by bottoming the nut against the clamp bushing. The cable grip was modified from previous designs so that all clamping action is performed prior to insertion into the connector shell. This simplifies the assembly of the connector. A chamber between the rear of the terminus assembly and the end of the cable jacket allows movement of the jewel ferrules backward during mating. The chamber will also allow for fiber slack to prevent damage when the tensile load is applied to the cable. The fibers move 1.90 mm axially under a 180 kg load. This "flex chamber" will allow for a relatively large bend radius of the fiber to reduce bend losses. Both the Cannon and the Hughes designs provided this space.

3.2.4 Hughes Connector Development

In May 1980, contract cost adherance dictated a reduction in the quantity of hardware deliverables.

Because of additional development and consequent delay necessary to supply the ITT Cannon connector, ITT EOPD with the support of CECOM, placed a purchase order with Hughes Aircraft Company, Connecting Devices Division, in Irvine, California. The purchase order specified all hardware and termination of the connectors to the final cable design produced by ITT EOPD. An additional purchase order was placed for the connector qualification testing to the performed by Hughes in accordance with the test plan shown in Appendix B.

3.2.4.1 Hughes Connector Configuration

The Hughes six-way hermaphoditic connector is a rugged, passivated surface aluminum connector suitable for the tactical environment. The channels are optically separated to prevent crosstalk. The surface is readily cleanable with clear water. The design is waterproof. The coupling nut of each connector can be retracted to allow the coupling nut of the mating half to fasten to the mating threads. The keying and the use of alternating male and female contacts provide optical path continuity regardless of cable direction. Dust covers are available and were provided with the hardware delivered to this contract. A cutaway illustration of the hermaphorditic six-channel connector is shown in Figure 3.2.4.1-1.

The bulkhead receptacle connector supplied with the pigtail assemblies is fully mateable with the hermaphroditic connectors, but is not fully environmentally sealed. A cutaway illustration is shown in Figure 3.2.4.1-2.

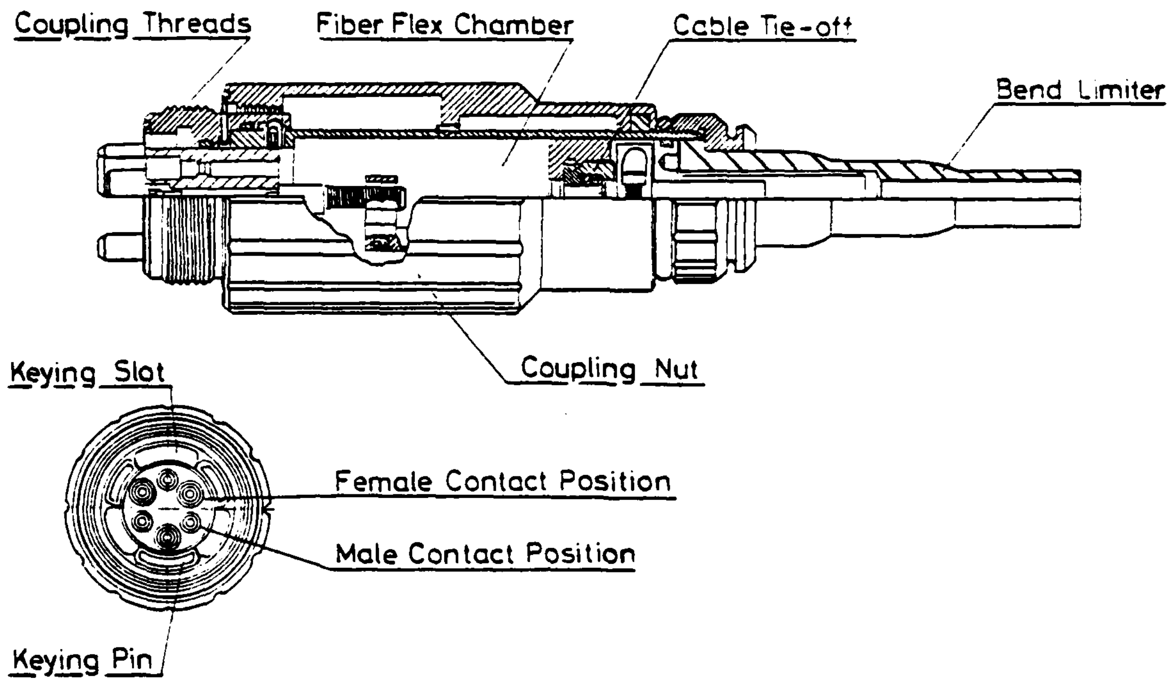

Figure 3.2.4.1-1. Fiber Optic Connector, Hermaphroditic, Six-Channel.

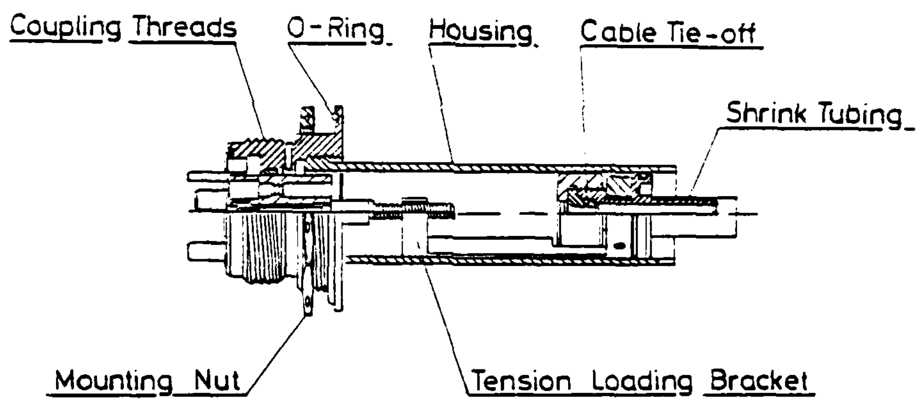

Figure 3.2.4.1-2. Fiber Optic Bulkhead Receptacle, Hermaphroditic, Six-Channel.

3.2.4.2 Terminal and Assembly

The Hughes terminal is shown in Figure 3.2.4.2-1. The procedure for terminating the Hughes connector with the ultra low loss cable was developed and documented. A copy of the procedure is included as part of Appendix C. A problem with the terminating procedure was discovered during temperature cycling.

The problem found in terminating the fibers with the pins was either protrusion of the fiber due to fracture of the epoxy to glass bond at the terminal jack or fracturing of the fiber during temperature cycling. This presumably was the cause of the fractured fiber in the connector contact of the third cable of CLIN 0005 cable as failures could be produced by temperature cycling terminal assembled this way.

The mechanism of failure was differential expansion and contraction in the termination. The termination technique consisted of step stripping the fibers and epoxying both ends. Illustrations are shown in Figures 3.2.4.2-2 and 3.2.4.2-3. During temperature cycling sufficient stress was built up to fracture the fiber in the unsupported area, or, if the fiber epoxy interface fractures, the fiber was forced to protrude.

The solution was to apply epoxy to the full fiber length, omitting the step stripping of the RTV silicone buffers. Ths solution

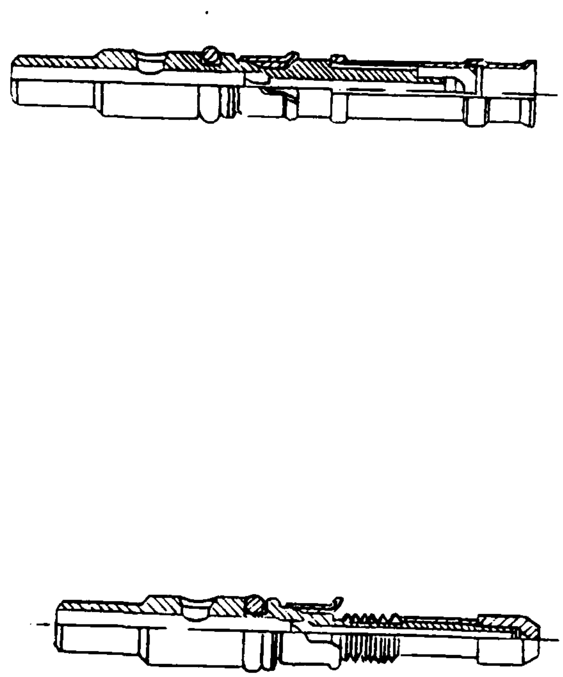

Figure 3.2.4.2-1. Hughes Terminal.

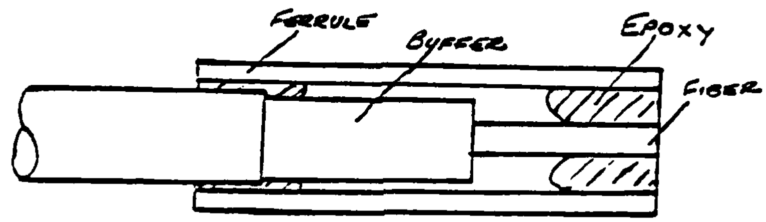

Figure 3.2.4.2-2. Old Technique.

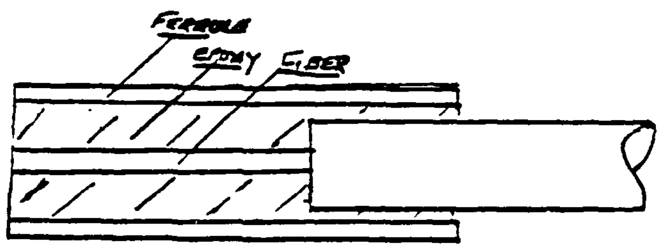

Figure 3.2.4.2-3. New Technique Using Epo-tek 330D.

performs two functions. This first is to prevent flexure of the fibers under stress reducing the buckling problem. The second is to increaase the fiber epoxy bond area, reducing the chance of protrusion. Test results comparing the two techniques are shown in Table 3.2.4.2-1. The new technique reduced failures significantly as shown by test.

Cable samples were terminated using both the old Hughes method and the ITT method. The old method produced failures which confirmed their earlier experience. The new technique was performed by each company represented. The only failure occurred on a first attempt by ITT personnel to demonstrate. The remainder were satisfactory.

3.2.4.3 Hughes Connector Assembly Strain Relief

The Hughes clamping provides both an O-ring and a positive metal-to-metal clamping mechanism. The O-ring is shown as item a in Figure 3.2.4.3-1. The metal-to-metal surface is between the jam-nut (item b) and locking sleeve (item c). When the cable is dressed for termination, sufficient length is combed out to be laid back over the front face of the locking sleeve and over the O-ring, then back over the front face making two thicknesses of the Kevlar®. The jamnut is then tightened, pulling the inner sleeve (item d) against the locking sleeve, captivating the Kevlar®. This arrangement has been proof-tested to 400 lb in the ultra low loss cable assembly.

Table 3.2.4.2-1. Test Results.

I. Old Hughes Terminations

	Blue	Green	Orange	Gray	White	Brown
Hughes	2.5 mm	✓	✓	2.5 mm	✓	✓
Hughes	0.025 mm	✓	✓	✓	✓	✓

✓ = Passed

2.5 mm = Fiber extended 2.5 mm

Blank means test not done; no breaks occurred

II. New Terminations

Assembly By	Blue	Postcycling Data Green	Orange	Gray	White	Brown
EOPD		✓	✓	✓	✓	
EOPD	≈0.1 mm	✓		✓		
Hughes	✓	✓		✓		
Hughes						
GTE	✓	✓		✓		
GTE	✓					
EOPD	✓	✓	✓		✓	✓
EOPD	✓	✓	✓	✓	✓	✓

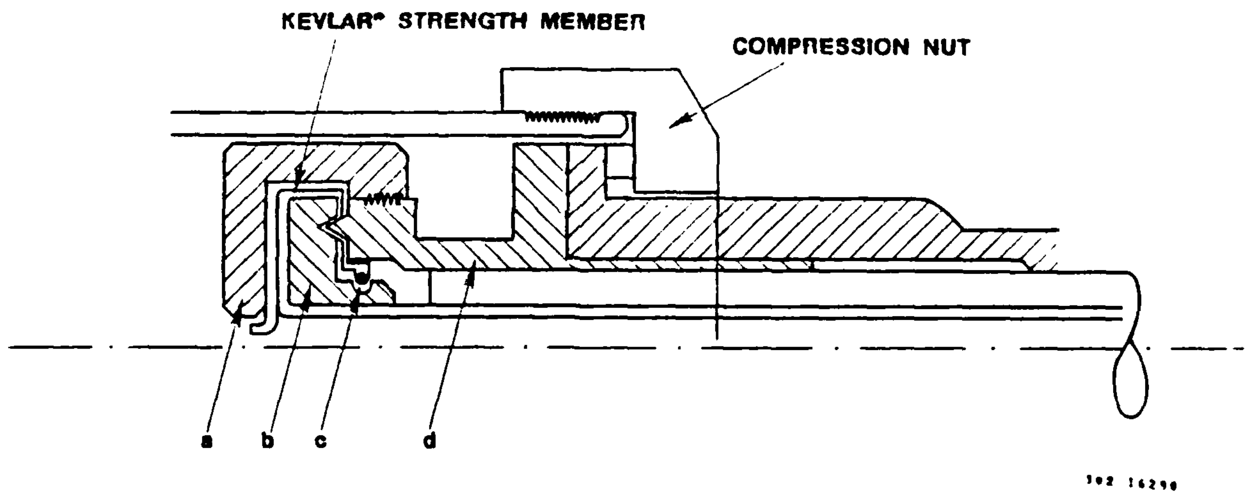

Figure 3.2.4.3-1. Strain Relief Mechanism in Hughes Connector.

3.2.4.5 Hermaphroditic Channel Continuity

The connector design delivered in all CLIN items was the Hughes design. The Hughes connector assembly accomplished hermaphrodicity by use of a coupling nut which could either be retracted out of the way or threaded forward to couple with the mating connector assembly. Contacts 1, 3, and 5 are sockets and 2, 4, and 6 are receptacles. To be hermaphroditic a pin-to-socket channel for the two mating halves must be continuous regardless of the direction of the cable when coupling is done. This is accomplished in the Hughes design by keying the connector assembly with coupling nut back to the mating half with coupling nut forward so that pins mate with the sockets 180° off. The hookup list for the contacts reads 1 to 4 and 3 to 6.

3.2.4.6 Connector Mating Characteristics and Field Maintenance

The connector assembly units are suitable for connector mating under tactical field conditions and are protected prior to mating by the protective dust cap. The mating faces of the connector have no crosstalk between adjacent optical paths due to isolated channel design. The optical mating faces are suitably protected to prevent permanent degradation of light transfer between mating connectors as a result of repeated matings, exposure to moisture, water immersion, dirt, dust, sand, salt spray, and temperature extremes. The interface of the jeweled ferrules is washable with water or lens cleaning fluid. The interface is not readily accessible to brushes, cotton tip applicators, cloths, probes, or other cleaning devices which could scratch or chip the ends of the fibers. In the event foreign matter which cannot be washed out enters the guide sleeve of the terminus, the connector can and should be disassembled by a trained technician, fiber ends cleaned and inspected for damage, and then reassembled. Because of the size and position of the male and female sleeves in the connector, only extreme misuse would cause damage or degradation. The interface termini are protected by the shell.

3.3 Cable Assembly Deliverables

The cable assemblies to be delivered for test under this contrast are three-1 km assemblies (CLIN 000).

3.3.1 Connector/Cable Assembly Test Results for CLIN 0004 and CLIN 0005

The pigtail assemblies were tested in accordance with the connector development plan (Appendix A). The pigtails were tested in pairs with an hermaphroditic cable connector interfaced with a bulkhead connector. The pairs were identified as samples 1 through 6. Each pair was then subjected to a unique sequence of tests. A summary of the test results is shown in Table 3.3.1-1. The test report is included as Appendix B. The results are within performance goals except in fluid immersion of the bulkhead connector, and the crosstalk test was deleted since the Hughes connector channels are separate and closed precluding the possibility

Table 3.3.1-1. Summary Compliance Chart for Hughes Connector Tests.

Step	Goal	1	2	3	4	5	6
1) Examination	-	Pass	Pass	Pass	Pass	Pass	Pass
2) Coupling loss	1.5 dB	≤1.27	≤1.65	1.60	≤1.56	≤1.46	≤1.16
3) Flex life	1000~	-	-	-	-	Pass	-
4) Twist	1000~	-	-	-	-	-	Pass
5) Mating durability	1000~	Pass	Pass	Pass	Pass	-	-
6) Examination	Pass	Pass	Pass	Pass	Pass	Pass	Pass
7) Coupling loss	1.5 dB	Pass <1.48	≤1.63	1.60	≤1.55	≤1.33	≤1.15
8) Twist	1000 cycles	-	-	-	Pass	-	-
9) Immersion	No degradation	Fail*	-	Fail*	-	-	-
10) Cable retention	400 lb	-	Pass (400 lb)	-	-	-	-
11) Examination	No damage	See*	Pass	See*	Pass	-	-
12) Coupling loss	≤1.5 dB	See* 5 ≤2 dB 1 ≥3 dB	≤1.48	See* 5 ≤2 dB 1 ≥2 dB	≤1.62	-	-
13) Cable retention	400 lb	Pass	-	-		-	-
14) Flex life	1000~	-	-	Pass	-	-	-
15) Crosstalk	-	Pass	See**	-	-	-	-
16) Examination	No damage	Pass	-	Pass	-	-	-
17) Coupling loss	1.5 dB	Pass ≤1.94	-	≤1.63		-	-
18) Crosstalk	-	See**	-		-	-	-

Note: (-) indicates not required on this subgroup. A subgroup is one hermaphroditic and one bulkhead connector mated.

*Leakage occurred among the [illegible]. This connector is not designed for immersion resistance, but the other paths hold. Cleaning and recoupling brought losses within limit and test was continued.

**Not applicable to Hughes connector with separate channels.

of crosstalk. In the case of the bulkhead connector, leakage occurred along the backshell threads, an area which is within the electronics enclosure where standing water would render the system inoperative and hence is not a realistic field condition. For the purpose of evaluation the test was performed and the surface washed and the test sequence continued to show cleavability. Coupling loss measurements were allowed to go to 2.0 dB as a goal. Readings exceeded 2.0 dB only in 2 out of 12 channels after immersion. The average of readings was within 0-1.5 dB.

3.3.2 Final Cable Assembly Data

The final deliverable cable assemblies were three 1 km cables with connectors. A bubble was found in one fiber of one cable at 300 m. The bubble was found with an optical time domain reflectometer (OTDR) as a localized reflection. The cable was cut and reterminated to remove the defect. Final delivery of two 1 km and one 700 m cable assembly was made. Measurements were made on the fibers and cables prior to assembly of the terminations, and the optical properties of the finished assemblies at room temperature and at -55°C. This latter measurement was done to assure that the fiber screening had eliminated the cold temperature attenuation increase.

Tables 3.3.2-1 through 3.3.2-3 contains the optical properties measured at each stage of development: as raw fiber, in cable, and as finished assembly.

Table 3.3.2-1. Cable Properties (at λ = 0.85 nm).

Cable 070281-4C-2

Fiber Id	Blue	Orange	Green	Brown	Slate	White
Fiber Properties	HG090266	HG090295	HG090241	HG090303	HG090241	HG090229
Attenuation, R.T. (dB/km)	3.22	2.85	3.57	3.09	3.66	3.03
Attenution change, -55°C (dB/km)	0.75	0.31	0.66	0.27	0.75	0.73
Dispersion (ns/km)	1.34	1.63	0.37	1.09	0.37	0.36
Cable Properties						
Attenuation, R.T. (dB/km)	3.21	3.08	3.01	3.24	3.08	3.33
Attenuation change, (dB/km)	1.95	0.76	0.86	0.63	0.47	0.93
Dispersion (ns/km)	0.61	1.06	1.34	0.52	0.67	1.03
Cable Assembly (1109 m)						
Attenuation, R.T. (dB/km)	6.21	5.31	4.69	5.60	5.71	5.17
Attenuation, -55°C (dB/km)	0.83	0.91	1.48	1.76	0.29	1.26
Connector, two mated pair	3.00	2.23	1.68	3.36	2.63	1.84

Table 3.3.2-1. Cable Properties at λ = 0.85 nm (continued).

Cable 061781-4C-1

Fiber Id	Blue	Orange	Green	Brown	Slate	White
Fiber Properties	HG090367	HG090373	HG090353	HG090330	HG090361	HG090258
Attenuation, R.T. (dB/km)	3.15	3.34	3.56	4.12	3.28	3.47
Attenution change, -55°C (dB/km)	1.85	1.10	1.09	1.09	1.27	1.30
Dispersion (ns/km)	0.54	0.65	0.89	0.38	0.33	0.62
Cable Properties						
Attenuation, R.T. (dB/km)	3.33	3.15	3.80	3.80	3.16	4.23
Attenuation change, (dB/km)	1.40	1.20	1.62	1.62	0.84	0.64
Dispersion (ns/km)	0.65	0.88	0.58	0.58	0.51	0.60
Cable Assembly (709 m)						
Attenuation, R.T. (dB/km)	7.48	5.80	6.79	6.79	6.51	6.20
Attenuation, -55°C (dB/km)	2.58	2.38	1.60	4.30	1.40	3.66
Connector, two mated pair	4.15	2.65	2.99	2.99	3.35	1.93

Table 3.3.2-1. Cable Properties at λ = 0.85 nm (continued).

Cable 070181-4C-1

Fiber Id	Blue	Orange	Green	Brown	Slate	White
Fiber Properties	HG090249	HG090290	HG090242	HG090290	HG090242	HG090200
Attenuation, R.T. (dB/km)	3.25	3.05	3.22	1.45	3.04	3.39
Attenution increase, -55°C (dB/km)	0.75	0.31	0.66	0.27	0.75	0.73
Dispersion (ns/km)	1.34	1.63	0.37	1.09	0.37	0.36
Cable Properties						
Attenuation, R.T. (dB/km)	3.34	3.26	3.24	3.41	3.15	3.28
Attenuation change, (dB/km)	1.80	1.86	0.80	0.38	0.68	0.96
Dispersion (ns/km)	1.15	1.97	0.51	0.55	1.50	0.91
Cable Assembly (709 m)						
Attenuation, R.T. (dB/km)	5.45	7.78	5.20	5.37	5.92	5.10
Attenuation change, -55°C (dB/km)	1.40	1.20	0.56	1.62	0.84	0.64
Connector loss (two mated pair)	2.11	4.52	1.96	1.96	2.77	1.73

4.0 CONCLUSIONS

The cable assembly developed for this contract meets the functional goals of the contract. This was demonstrated not only in the tests performed but in tactical applications for which assemblies to this design have been procured.

The channel loss was within the fiber loss plus interface connector loss goal. The bulkhead connector to hermaphroditic connector interface averaged under the 1.5 dB goal but did not meet the immersion resistance goal. Water penetrated along the backshell threads when under test. Immersion resistance is important in a tactical cable which can be dropped in standing water or flooded in storage. The hermaphroditic connector is a true tactical connector and passed immersion. The bulkhead receptable is panel mounted inside a shelter and will not be immersed the standing water while the mated hermaphroditic halves will. Consequently, the entire cable interconnect system, from module to module, can be expected to perform under the tactical field conditions.

Nuclear hardening was studied but not achieved under this contract. The radiation dosage produced very high transient attenuation which gradually decayed to a permanent attenuation which was higher then initial attenuation. The effect was measured and recorded.

The connector selected is made by Hughes, has isolated, crosstalk free channels, has corrosion resistant finish, and is rugged for tactical applications. Serviceability requires a protected area when the connector is terminated. This can be provided by any convenient portable shelter. The connector can be easily mated and cleaned under exposed conditions. The connector has a non-glass finish to make enemy detection difficult. A dust cap is provided to preclude damage during storage or deployment prior to coupling.

The areas where improvement can be directed are as follows:

- Assembly and repair of the cable assembly under adverse field conditions
- Nuclear hardening of the fiber - This will require some closer definition of dosages and rates since the answer to one level and rate may not be optimal for another
- Blast hardening of the cable - Both heat flash and wind overpressure can be present which would disable this design
- Reduction of size and weight of the connector

Finally, the cable assembly is fully usable with no further refinement.

5.0 REFERENCES

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